AN EVALUATION OF HABITAT CONDITIONS AND SPECIES COMPOSITION ABOVE, IN, AND BELOW THE ATOMIZER FALLS COMPLEX OF THE LITTLE COLORADO RIVER

by

William Patrick Mattes

A Thesis Submitted to the Faculty of the

SCHOOL OF RENEWABLE NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN WILDLIFE AND FISHERIES SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 9 3

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgement the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the Author.

SIGNED: William P Matter

APPROVAL BY THESIS COMMITTEE

This thesis has been approved on the date shown below:

O. Eugene Maughan — 11/15/93

O. E. Maughan, Ph.D
Professor, Wildlife and Fisheries Science
Date

William J. Matter — 11/15/93

W. J. Matter, Ph.D
Associate Professor, Wildlife and Fisheries Science
Date

Owen T. Gorman — 11/8/93

O. T. Gorman, Ph.D
Fisheries Biologist
U. S. Fish and Wildlife Service
Date

AN EVALUATION OF HABITAT CONDITIONS AND SPECIES COMPOSITION
ABOVE, IN, AND BELOW THE ATOMIZER FALLS COMPLEX
OF THE LITTLE COLORADO RIVER

William Patrick Mattes, M.S.
The University of Arizona, 1993
Director: O. Eugene Maughan

Water chemistry (carbon dioxide, pH, alkalinity, hardness, and turbidity) and physical habitat (depth, velocity and substrate) change gradually on the Little Colorado River, Arizona, downstream from Blue Springs (river kilometer 11.40 to 21.06). Fish distribution is correlated with changes in water chemistry and physical habitat. Monthly trends in water chemistry and physical habitat depended upon seasonal conditions: summer rain runoff (July and September 1992), spring runoff (April 1993), and base flow (June and July 1993).

Acknowledgements

I sincerely thank O. Eugene Maughan my committee chairperson for his reviews of previous reports and this document and for his open door when things looked bleak. I thank committee member William Matter for his comments on this and other documents and for his consultation throughout my graduate school experience. I thank committee member Owen Gorman of the U.S. Fish and Wildlife Service for his ideas on study design and for reviews of this document.

I thank the many agencies and the people behind them that made this project possible namely Gloria Notah of the Navajo Nation Fish and Wildlife, and Jim Hansen and Stuart Leon of the U.S. Fish and Wildlife Service.

Many people helped to make this project run smoothly and contributed to getting the work done. Foremost, I thank John Seals of the U.S. Fish and Wildlife Service in Flagstaff for coordinating my gear needs. I also thank Ralph Lim for his technical assistance and for hanging on even when the flood waters persisted. I thank Brian Dorr for his assistance both in the field and behind the computer. Finally, I thank the many other technicians that helped with data entry and editing.

I am grateful to the other members of the 'canyon crew' Nathan Allan, Ted Otis, and Steve Weiss for the many hours of combined research and idea sharing in the catacombs of Bio-East.

Finally, I would like to acknowledge my family. I am forever indebted to my wife Lorri, who supported me financially as well as psychologically throughout my graduate experience and I thank my son William Andrew for bringing me an avenue of stress relief by allowing me to play daddy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES-*Continued*

LIST OF FIGURES-*Continued*

LIST OF TABLES

LIST OF TABLES-*Continued*

LIST OF TABLES-*Continued*

ABSTRACT

Water chemistry (carbon dioxide, pH, alkalinity, hardness, and turbidity) and physical habitat (depth, velocity and substrate) change gradually on the Little Colorado River, Arizona, downstream from Blue Springs (river kilometer 11.40 to 21.06). Fish distribution is correlated with changes in water chemistry and physical habitat. Monthly trends in water chemistry and physical habitat depended upon seasonal conditions: summer rain runoff (July and September 1992), spring runoff (April 1993), and base flow (June and July 1993).

INTRODUCTION

The humpback chub (Gila cypha) is a minnow (family Cyprinidae; Eddy and Underhill 1984) that is endemic to the canyons of the Colorado River (Rinne and Minckley 1991). The humpback chub is adapted to life in swift water (Minckley 1973, Holden and Stalnaker 1975, Behnke and Benson 1980, Keading et al. 1990, Carothers and Brown 1991, Rinne and Minckley 1991) It is often found near the stream bottom (Miller 1946) and near submerged rocks in swift water, where there are rapid changes in current velocity and direction (Keading et al. 1990). Adaptations for life in swift water include large falcate fins, a specialized nuchal hump, inferior mouth, and a dorso-ventrally flattened head (Minckley 1973).

The largest known population of humpback chub in the Grand Canyon occurs at the confluence of the Little Colorado River (LCR) and the Colorado River (Keading and Zimmerman 1983, Carothers and Brown 1991). Maintenance of the population in the LCR is assumed to be essential to the future existence of the species (Suttkus and Clemmer 1980, Maddux et al. 1987, USFWS 1990), because Glen Canyon Dam (about 75 miles or 114 km upstream) appears to have greatly reduced the historic range of this species (Suttkus and Clemmer 1980, USDI 1988, Carothers and Brown 1991).

The main cause for the decline of humpback chub is postulated to be the closure of Glen Canyon Dam. The closure of the dam changed the Colorado River from a highly fluctuating warm water system to a cold water system with comparatively steady flows (Maddux et al. 1987). Hamman (1982) showed that survival of early life stages of humpback chub were severely limited at temperatures below 13° C, and Keading and Zimmerman (1983) showed that such temperatures limited the survival of early life stages of humpback chub around the confluence of the LCR and Colorado River.

Humpback chub appear to prefer swift, relatively warm water. However, they use a variety of habitats. The USFWS (1990) found adult humpback chub in the Upper Colorado River Basin in water < 9.1 m deep over silt, sand, boulder, and bedrock substrate with water velocities usually < 30 cm/s. Adult humpback chub in the LCR have been taken in pools adjacent to eddies, large pools with little or no current, and areas below travertine ($CaCO_3$) dams (USFWS 1990). Maddux et al. (1987) suggested that higher turbidity in the major tributaries of the Colorado River, such as the LCR, Paria River, and Kanab Creek may facilitate their use by humpback chub and other native fish.

Keading and Zimmerman (1983) and Carothers and Minckley (1980) found humpback chub, flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus (Pantosteus) discobolus*), carp (*Cyprinus carpio*), channel catfish (*Ictalurus punctatus*) and rainbow trout (*Oncorhynchus *mykiss*) in the lower 14 km and speckled dace (*Rhinichthys osculus*), fathead minnow (*Pimephales promelas*), and plains killifish (*Fundulus zebrinus*) throughout the lower 21 km of the LCR.

<u>Objectives</u>

This project is a subset of the Glen Canyon Environmental Studies (GCES) work on the Colorado River and its tributaries in the Grand Canyon. GCES was established, in part, to study the effects of Glen Canyon Dam on environmental conditions and biota downstream. Conservation measure 5 issued by GCES states the need to "identify and quantify preferred habitats of juvenile and adult humpback chub and other fish species in the LCR".

On the LCR water chemistry, macrohabitat, microhabitat, and fish distribution may change relatively quickly in the area from 11.4 km to 21.06 km. The specific objectives of my study were to:

1) Determine differences in the chemical conditions in several areas on the LCR between 11.4 km and 21.06 km.
2) Determine differences in habitat availability in several areas on the LCR between 11.4 km and 21.06 km.
3) Determine the differences in distribution and habitat use of fish in several areas on the LCR between 11.4 km and 21.06 km.

Description of Study Area

The LCR basin covers an area of about 69,807 km^2 (USDA 1981a), and the river is 412 km in total length (Maddux et al. 1987). This area has an average annual rainfall of 20.25 cm. The wettest months are July and August and the driest months are May and June. Air temperatures range from an average 1° C in January to 27° C in July (USDA 1981b). Terrestrial areas support Great Basin Desert Scrub; characterized by low growing vegetation that is often divided into large stands of single species (USDA 1981c).

The LCR becomes perennial below Blue Springs at about 21 km above the confluence and flows at 5.94 m^3/s (220 f^3/s) (Johnson and Sanderson 1968, Maddux et al. 1987); there is some indication that the river was perennial above Blue Springs before the 1940's (Hereford 1984). Water from Blue Springs is mineralized, rich in free carbon dioxide, and has high temperatures compared to waters emanating from surface runoff (Cole 1975).

METHODS

Description of the Study Sites

Study areas (1-15) were established on the LCR between Big Canyon and 60 m upstream of Blue Springs (Table 1). Area 1 was a spring entering the LCR from Big Canyon. Areas 2-4 were located downstream of major travertine dams. Areas 5-8 were between major travertine dams. Areas 9-15 were

Table 1. Location (river kilometer) and description of each study area on the Little Colorado River.

Area Number	River Kilometer	Area
1	10	Big Canyon Spring
2	11.4-11.6	USFWS upper Salt Trail Camp Study area
3	11.8-12.6	Mecca Falls to Triple Drop Falls
4	13	The Crossing
5	13.8-13.9	Below Atomizer Falls
6	14.0-14.3	Between Atomizer and Upper Atomizer Falls
7	14.4-14.5	Between Upper Atomizer and Chute Falls
8	14.6-14.9	Above Chute Falls
9	16.0-16.9	16 kilometer area
10	17.0-17.9	17 kilometer area
11	18.0-18.9	18 kilometer area
12	19.0-19.9	19 kilometer area
13	20.0-20.9	20 kilometer area
14	21	Blue Springs
15	21.06	Flow entering above Blue Springs

upstream of these travertine dams. Water chemistry was evaluated at areas 1-15. Habitat conditions were evaluated at areas 5-12, and area 14. Fish distribution was evaluated at areas 1, 2, and 5-15. Humpback chub were abundant in area 5 and areas downstream, present in low densities in areas 6 and 7, and absent from area 8 and upstream (Minkley 1977, Kaeding and Zimmerman 1983).

There are a series of 3 high (> 1.5 m) travertine dams between 13.9 and 14.6 km on the LCR which I refer to as the Atomizer Falls complex. The names and placement of these dams in upstream order are as follows; Atomizer Falls (13.98 km), Upper Atomizer Falls (14.34 km), and Chute Falls (14.60 km) (Figure 1). These dams separate areas 5, 6, 7, and 8.

Area 5 consisted of a pool-run complex directly below Atomizer Falls (13.8 to 13.9 km). The water was turbid during base flow due to $CaCO_3$ percipitation. Sand and travertine were the dominant substrate types. Area 6 was between Upper Atomizer Falls and Atomizer Falls (14 to 14.3 km). Area 6 consisted of two pool-run complexes separated by a small (< 0.5 m) travertine dam. The water was turbid during base flow although not as turbid as in area 5. Sand and travertine were the dominant substrate types. Area 7 was between Upper Atomizer Falls and Chute Falls and consisted of a pool-run complex directly below Chute Falls

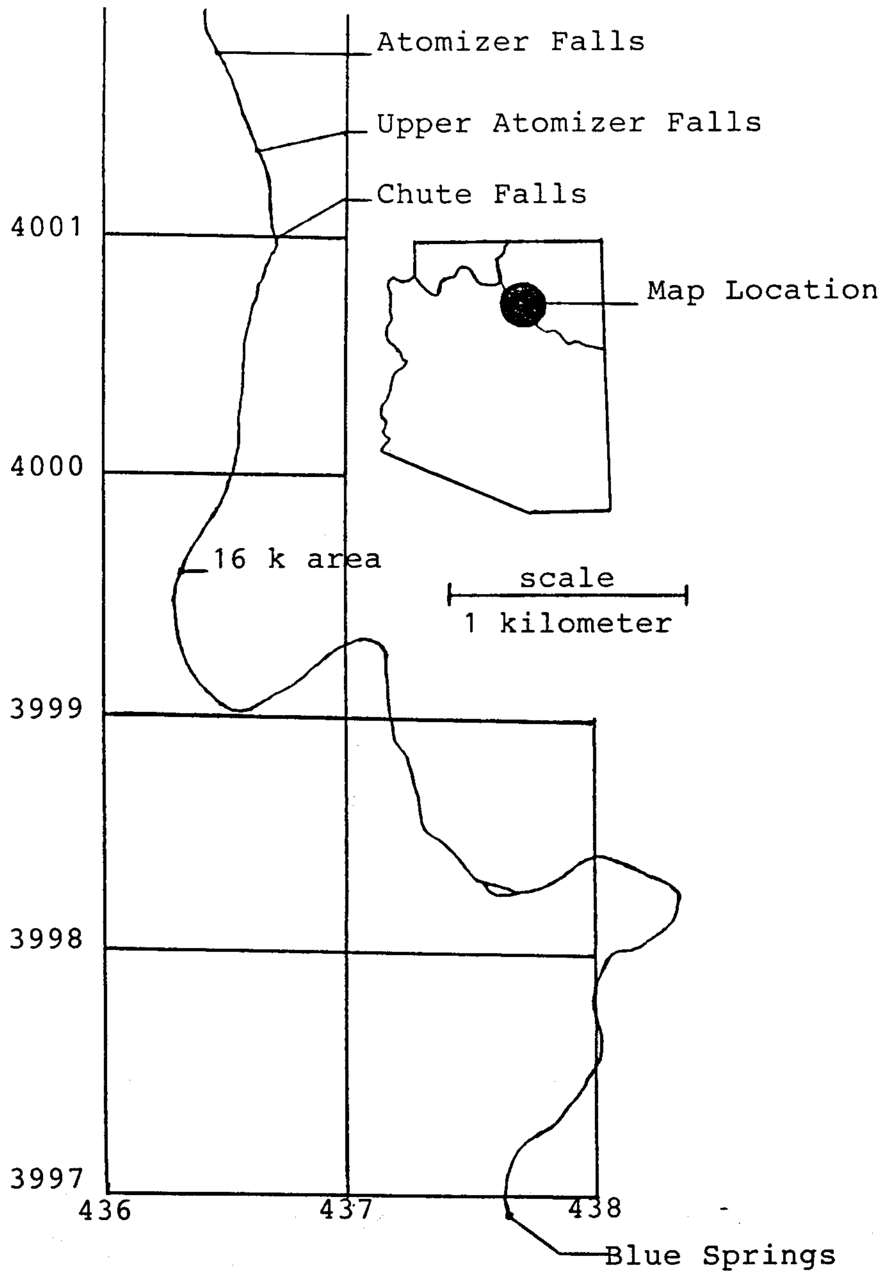


Figure 1. Little Colorado River, Coconino county, Arizona, from Blue Springs to Atomizer Falls, adapted from USGS (1988a) and USGS (1988b).

(14.4 to 14.5 km). The water was clear during base flow and the dominant substrates were sand and travertine. Area 8 was directly above Chute Falls and consisted of a riffle and a pool-run complex directly below a travertine dam (14.6 to 14.8 km). Water was clear and the dominant substrates were sand and travertine.

Area 9 was at the upper terminus of a large sandy stretch of river above Chute Falls (16 to 16.9 km). Area 9 consisted of a small travertine dam and a pool-run complex. Water was clear during base flow and the dominant substrates were sand and travertine.

Area 10 was between 17 and 18 km, area 11 between 18 and 19 km, area 12 between 19 and 20 km, area 13 between 20 and 21 km, area 14 was at Blue Springs and area 15 was a 60-m stretch above Blue Springs.

Habitat Assessment

Water Chemistry

Transects were established every 20 m throughout the lower 21 km on the LCR. Water chemistry parameters were collected at these 20-m transects. Temperature, conductivity, pH, and dissolved oxygen were measured with a portable water quality analyzer. Carbon dioxide, alkalinity, and hardness were measured with a HACH digital titrator (model 16900-01). Carbon dioxide (mg/l of CO_2) was measured by titrating a 100-ml sample to a phenolphthalein end point with sodium hydroxide (3.636 N). Total alkalinity (mg/l as $CaCO_3$) was measured by titrating a 100-ml sample with 1.600 N sulfuric acid to the bromcresol green-methyl red end point (pH 4.5). Total hardness (mg/l as $CaCO_3$) was measured by titrating a 100-ml sample with 0.0800 N EDTA to a pure blue color. More detailed explanations of the above chemical titrations can be found in the HACH Water Analysis Handbook (HACH 1989). Turbidity was measured with a Secchi disk or with a standard turbidity meter.

Macrohabitat

Macrohabitat was characterized by measuring depth, velocity and substrate every 1 m across transects (e.g., Gorman and Karr 1978). Depth was measured with a metric wading rod. Velocity classes were defined following Gorman and Karr (1978) (Table 2). Substrate was classified according to the definitions given in Table 3. Stream width was measured at each transect.

Microhabitat

Microhabitat availability and use were determined for each area by measuring depth, velocity, and substrate conditions at the specific point of sampling (by net, trap, or seine) at the time of net or trap placement, or immediately following a seine haul. A 0.5-m grid (10 to 20 points) was used to define microhabitat around mini-hoop nets (Figure 2a), a 0.1-m grid (5 points) was used to define

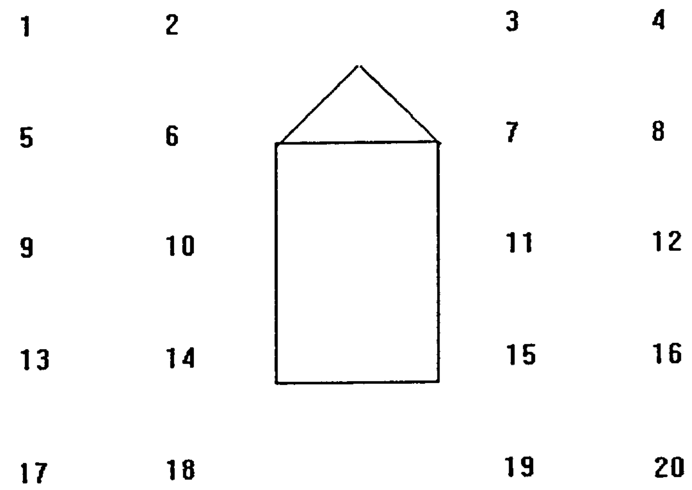
Table 2. Velocity categories (Gorman and Karr 1978), used to characterize habitat on the Little Colorado River 1992-1993.

Velocity Category	Definition
0	< 0.02 m/s
1	0.02-0.10 m/s
2	0.10-0.30 m/s
3	0.30-0.70 m/s
4	0.70-1.20 m/s
5	> 1.20 m/s
ISL	points out of water

Table 3. Substrate catagories used to describe habitat in the Little Colorado River, 1992-1993.

Substrate Category	Definition	Size
0	silt	< 0.06 mm
1	silty-sand	0.06-0.10 mm
2	sand	0.10-2.0 mm
3	gravel	2.0-16 mm
4	pebble	16-32 mm
5	rock	32-100 mm
6	cobble	100-256 mm
7	small boulder	256-1000 mm
8	boulder	1-3 m
9	large boulder	> 3 m
10	travertine	$CaCO_3$ cemented (i.e. dams)
11	bedrock	canyon walls

a)



b)

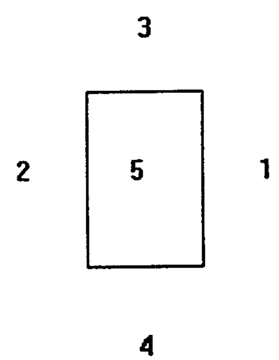


Figure 2. Point measurement grids used for assessing microhabitat of a) mini-hoop nets and b) minnow traps, on the Little Colorado River.

microhabitat around minnow traps (Figure 2b), and 3 transects (points measured every 1 m or 0.5 m if the area swept was less than 3 m wide) were used to define microhabitat in each area seined.

Fish capture

Mini-hoop nets, minnow traps, seines, underwater observation, and bank observation were used to measure fish distribution and abundance. Mini-hoop nets measured 55 x 150 cm with 1/4-inch mesh, minnow traps were 19 x 42 cm with 1/4-inch mesh, and the seine used was 10 m x 1.5 m with 1/4-inch mesh.

Nets and traps were deployed along established 20-m transects in the study areas. Mini-hoop nets were set about 3 to 5 m apart across the entire width of the stream. Minnow traps were used in shallow (<1 m) near shore areas. Generally nets and traps were set and microhabitat data taken between 1100 and 1400 hours. Fish were collected from the nets/traps between 1600 and 1900 hours and again between 0700 and 1000 hours the following day.

Limited seining was done in shallow (<1.5 m) near shore areas where there were silt or sand substrates. Seine hauls were made in the vicinity of established 20-m transects. I recorded species and length for all fish caught. Sex, weight and tag information were taken from adult (> 150 mm) humpback chub and suckers.

I used two techniques to obtain underwater observations of fish. In areas 7, 8, and 9 one person gathered qualitative data on fish distribution. The person entered the water downstream of the area to be observed and moved upstream and then downstream through the area. Areas selected for underwater observation were narrow (isolated by sandbars and travertine dams) and visibility was high.

Quantitative underwater data were gathered by using multiple observers in narrow (<15 m) pool/run areas. Three observers entered at the downstream end of the area and moved upstream through the area while looking only to the left. The first observer moved along the upstream right shoreline, the second observer was 3 m to the left of the first, and the third observer was 3 m to the left of the second observer. The length of stream surveyed varied from area to area.

Bank observations were made by walking upstream and noting the species, number and location of fish or by counting the number and location of fish within a grid. The grid was established by placing rocks instream where nets had been the previous day. Fish were allowed to acclimate to the grid for 30 minutes. Fish were allowed to acclimate to the observers for 10 minutes before observations were recorded. Observations were made on 4 sections of the 4 x 5 grid for mini-hoop nets, and 2 sections of the 2 x 2 grid for minnow traps. Sections to be surveyed were selected by picking random numbers from a hat with replacement. Each section was observed for 5-10 minutes. The observer reported the species of fish and their position in the water column to a recorder.

ANALYSIS

Water Chemistry

Analysis of variance (ANOVA, Norusis 1990) was used to evaluate mean water chemistry conditions (Table 4) from each area (alpha=0.05), under the H_0: the means for all areas are equal. To meet the assumptions of ANOVA the populations (water quality data) must be normally distributed and must have equal population variances (Ott 1988). There were minor departures from normality in the data but ANOVA tests were still quite robust (Kuehl consulting statistician personal communication, Ott 1988). Cochrans-C or Bartlett-Box F statistics were used to determine the homogeneity of variance for the populations sampled (Norusis 1990). There were minor departures from homogeneity. Minor departures from the assumption of homogeneous variance generally will not cause large changes in the efficiency of ANOVA testing (Kuehl consulting statistician, personal communication, Ito 1980). Therefore, data were analyzed as if they had homogeneous variances and were normally distributed.

Differences among means were further analyzed with the Tukey Honestly Significant Difference (HSD) multiple-comparison procedure, corrected for unequal sample sizes

Table 4. Water chemistry data (temperature in °C [temp]), conductivity (milli-Siemens [cond]), pH, dissolved oxygen (mg/l [D.O.]), carbon dioxide (mg/l [CO_2]), alkalinity (mg/l $CaCO_3$ [alk]), hardness (mg/l [hard]), Secchi disk reading (meters [turb]), and turbidity (NTU $CaCO_3$ units [NTU]) from the Little Colorado River.

Month	Year	Area	Parameters
July	1992	7,8,9	temp., cond., pH, D.O.
		7,8	turb.
August	1992	7	temp., cond., pH, D.O.
September	1992	7,9,10 11,12,15	temp., cond., pH, D.O.
		14	temp., cond., pH, D.O., CO_2, alk.
April	1993	5,6,7,8	temp., cond., pH, D.O., CO_2, alk., and hard.
June	1993	3,4,5, 6,7,8	temp., cond., pH, D.O., CO_2, alk., and hard.
		5,6,7,8	turb.
July	1993	1 - 15	temp., cond., pH, D.O., CO_2, alk., and hard.
		2 - 8	turb., NTU.

(Norusis 1990). This procedure uses a pairwise comparison of all treatment means based on an experiment-wise (alpha or Type I) error rate (Ott 1988). The probability of falsely finding one or more pairwise comparisons that were significant was specified at alpha=0.05.

Macrohabitat

Macrohabitat data were summarized for each month by area to give mean depth, modal velocity, modal substrate, and average width. Relative frequency histograms for depth, velocity, and substrate were developed for each sampling trip and area.

The cumulative frequencies for June 1993 were tested with the Kolmogorov-Smirnov two-sample test to determine if habitat parameters varied longitudinally. This analysis resulted in a series of dependent two-way tests (area 5 vs 6, 5 vs 7, 5 vs 8, 6 vs 7, 6 vs 8, 7 vs 8). The alpha level (p-value) was adjusted to ensure an experimental-wise error rate of 0.05 through division of the desired error rate (0.05) by the number of dependent comparisons (Eaton 1993, Vicky Meresky consulting statistician). This procedure resulted in a p-value of 0.0083.

Microhabitat and Fish Capture Data

Length frequency and catch per unit effort (CPUE) histograms were developed for speckled dace (Appendix A). CPUE was determined by dividing the total number of fish caught in a net or trap by the number of hours the net or trap was fished. The average of all nets and traps fished in an area represents a bin in the CPUE histogram.

Microhabitat data from all sampling grids were compiled to assess habitat sampled. Habitat data collected from all grids where fish were present were compiled to assess habitat use. The data were standardized by totaling the number of observations within each category for each parameter then dividing by the total for all categories for each parameter. The data were then multiplied by 100 to give percent. Frequency histograms were developed by month and area from the percent use and percent available data (Appendix B).

The habitat available vs used by speckled dace was compared statistically using the Kolmogorov-Smirnov two sample test (Slauson 1988). The hypotheses tested were:

H_o: The cumulative distribution of the depths sampled and the cumulative distribution of the depths used are the same.

H_o: The cumulative distribution of the velocities sampled and the cumulative distribution of the velocities used are the same.

H_o: The cumulative distribution of the substrates sampled and the cumulative distribution of the substrates used are the same.

RESULTS

Water Chemistry (ANOVA and HSD test results)

There was generally a gradient in pH, CO_2, alkalinity, hardness, and turbidity on the LCR from 11.40 km to 21.06 km. Monthly data did not always show these trends clearly.

July 1992

There were no significant differences in mean temperature nor in turbidity (Tables 5, 6 and 7), but there were significant differences in mean conductivity, pH, and dissolved oxygen among areas (Table 5).

HSD analysis showed that mean conductivity for area 9 was significantly higher than that for area 8 and that the mean for area 8 was significantly higher than that for area 7 (Table 8A). HSD analysis for pH showed the opposite trend; the mean pH for area 9 was significantly lower than that for area 8 and the mean for area 8 was significantly lower than that for area 7 (Table 8B). Dissolved oxygen did not follow a particular trend (Table 8C).

September 1992

There were significant differences among mean temperature, conductivity, pH, and dissolved oxygen (Tables 5 and 9) in areas 7, 9, 10, 11, 12, 14, and 15.

The mean conductivity (HSD analysis) in area 7 was significantly higher than the means in areas 10, 11, 12, 14, and 15; and the mean in area 9 was significantly higher than

Table 5. ANOVA for water chemistry data of all areas sampled on the Little Colorado River, July 1992, September 1992, April 1993, June 1993, July 1993.

Month Year	Var	Sum of Squares Between	Sum of Squares Within	Mean Square Between	Mean Sq Within	F	df B	df W	Signif
Jul 92	temp	6.89	38.86	3.44	0.68	5.05	2	57	0.2000
	cond	7.79	2.21	3.90	0.04	100	2	57	0.0000
	pH	2.33	2.03	1.16	0.04	32.65	2	57	0.0000
	D.O.	79.54	64.75	39.77	1.14	35.01	2	57	0.0000
Sep 92	temp	18.22	9.16	3.64	0.33	11.14	5	28	0.0000
	cond	7.94	1.34	1.59	0.05	33.07	5	28	0.0000
	pH	2.29	0.38	0.46	0.01	33.67	5	28	0.0000
	D.O.	1.44	2.54	0.29	0.09	3.17	5	28	0.0217
Apr 93	temp	2.76	51	0.92	3.42	0.27	3	15	0.8466
	cond	0.02	0.41	0.01	0.03	0.26	3	15	0.8524
	pH	0.28	0.11	0.09	0.01	12.3	3	15	0.0003
	D.O.	2.35	57	0.78	3.77	0.21	3	15	0.8896
	alk	907	4394	302	549	0.55	3	8	0.6618
	CO_2	9799	5210	3266	651	5.02	3	8	0.0303
	hard	2970	17667	990	2524	0.39	3	7	0.7626
Jun 93	temp	1.83	11.41	0.37	0.41	0.90	5	28	0.4956
	cond	1.68	1.15	0.34	0.04	8.20	5	28	0.0001
	pH	0.20	0.03	0.04	.001	33.31	5	28	0.0000
	D.O.	2.17	11.66	0.54	0.43	1.25	4	27	0.3107
	CO_2	38047	35642	7609	914	8.33	5	39	0.0000
	alk	1445	34824	482	1658	0.29	3	21	0.8318
	hard	19487	27189	6496	1295	5.02	3	21	0.0089
Jul 93	temp	60.94	108.2	5.54	4.01	1.38	11	27	0.2372
	cond	2.82	0.13	0.26	0.01	55.34	11	27	0.0000
	pH	5.47	0.12	0.50	.004	112.1	11	27	0.0000
	D.O.	20.50	20.47	1.86	0.76	2.46	11	27	0.0279
	CO_2	558605	24889	50782	372	137	11	67	0.0000
	alk	14629	3943	2926	493	5.94	3	8	0.0139

Table 6. Means of 4 water chemistry variables in areas 7, 8 and 9 on the Little Colorado River, July 1992.

Variable	Area	Mean	Standard Deviation	Cases
temp	7	21.9	0.97	32
	8	22.0	0.85	16
	9	21.5	0.53	12
cond	7	3.63	0.16	32
	8	4.00	0.23	16
	9	4.60	0.11	12
pH	7	7.52	0.25	32
	8	7.34	0.15	16
	9	7.05	0.14	12
D.O.	7	8.28	1.13	32
	8	6.37	0.96	16
	9	9.73	0.98	12

Table 7. Mean depth (meters) and associated standard deviations for Secchi disk readings from several areas on the Little Colorado River, July 1992, June 1993, and July 1993.

Month	Area	Mean	Std. dev.	Cases
July 1992	7	0.01	0.00	3
	8	0.01	0.00	1
June 1993	5	1.3	0.10	3
	6	2.2	0.92	6
	7	4.2	0.28	2
	8	3.5	0.00	1
July 1993	5	2.3	0.00	1
	6	5	0.00	1
	7	10	0.00	1
	8	17	0.00	1

Table 8. Tukey Honestly Significant Difference test of mean a) conductivity, b) pH, and c) oxygen for areas 7, 8 and 9 of the Little Colorado River, July 1992, (** = significant differences).

a)

Cond by Area		Area	Area	Area
		7	8	9
Mean	Area			
3.63	7			
4.00	8	**		
4.60	9	**	**	

b)

pH by Area		Area	Area	Area
		7	8	9
Mean	Area			
7.52	7			
7.34	8	**		
7.05	9	**	**	

c)

D.O. by Area		Area	Area	Area
		7	8	9
Mean	Area			
8.3	7		**	
6.4	8			
9.7	9	**	**	

Table 9. Means of 4 water chemistry variables in areas 7, 9, 10, 11, 12, 14 and 15, on the Little Colorado River, September 1992.

Variable	Area	Mean	Standard Deviation	Cases
temp	7	19.1	0.13	12
	9	18.5	0.85	13
	10	16.9	0.06	3
	11	20.3	0.57	2
	12	18.3	0.00	1
	14	18.0	0.00	1
	15	18.1	0.21	2
cond	7	3.22	0.17	12
	9	2.67	0.15	13
	10	2.17	0.01	3
	11	1.83	0.02	2
	12	1.97	0.00	1
	14	1.85	0.00	1
	15	1.97	0.86	2
pH	7	7.25	0.09	12
	9	6.78	0.12	13
	10	6.76	0.11	3
	11	6.67	0.16	2
	12	7.10	0.00	1
	14	6.55	0.00	1
	15	6.50	0.21	2
D.O.	7	7.8	0.17	12
	9	7.7	0.27	13
	10	7.5	0.29	3
	11	8.0	0.07	2
	12	6.8	0.00	1
	14	7.6	0.00	1
	15	7.4	1.06	2

Table 10. Tukey Honestly Significant Difference test of mean a) conductivity and b) pH, for all areas of the Little Colorado River, September 1992, (** = significant differences).

a)

Cond by Area		Area	Area	Area	Area	Area	Area	Area
Mean	Area	7	9	10	11	12	14	15
3.22	7							
2.67	9							
2.17	10	**						
1.83	11	**	**					
1.97	12	**						
1.85	14	**	**					
1.97	15	**						

b)

pH by Area		Area	Area	Area	Area	Area	Area	Area
Mean	Area	7	9	10	11	12	14	15
7.25	7							
6.78	9	**						
6.76	10	**						
6.68	11	**				**		
7.10	12							
6.55	14	**				**		
6.50	15	**				**		

Table 10. Tukey Honestly Significant Difference test of mean c) temperature and d) dissolved oxygen, for all areas of the Little Colorado River, September 1992, (** = significant differences).

c)

Temp by Area		Area	Area	Area	Area	Area	Area	Area
Mean	Area	7	9	10	11	12	14	15
19.1	7			**				
18.5	9							
16.9	10							
20.3	11			**		**	**	**
18.3	12							
18.0	14							
18.1	15							

d)

D.O. by Area		Area	Area	Area	Area	Area	Area	Area
Mean	Area	7	9	10	11	12	14	15
7.81	7							
7.66	9							
7.47	10							
7.95	11							
6.80	12	**			**			
7.60	14							
7.35	15							

the means in areas 11, 14, and 15 (Table 10A). The mean pH (HSD analysis) in area 7 was significantly higher than the means in all other areas except area 12. The mean pH in area 12 was significantly higher than that in areas 11, 14 and 15 (Table 10B). Temperature and dissolved oxygen followed no particular trend (Tables 10C and 10D).

April 1993

There were no significant differences (ANOVA) in mean temperature, conductivity, dissolved oxygen, alkalinity, and hardness in areas 5, 6, 7, and 8 during April (Tables 5 and 11). However, there were differences among the means for CO_2 and pH (Tables 5 and 11).

HSD analysis indicated that mean pH in area 5 was significantly higher than that in area 7, and 8, and that the pH in area 6 was significantly higher than that in area 8 (Table 12). The mean CO_2 for area 8 (HSD analysis) was significantly higher than that in area 5.

June 1993

There were no significant differences in mean temperature, alkalinity, and dissolved oxygen in areas 3, 4, 5, 6, 7, and 8 (Tables 5, 13). However, means for conductivity, pH, carbon dioxide, and hardness were significantly different (ANOVA) among areas (Table 5).

HSD analysis showed the mean conductivity for area 4 was significantly lower than those in area 3, 5, 6, 7, and 8

Table 11. Means of 7 water chemistry variables in areas 5,6,7, and 8, on the Little Colorado River, April 1993.

Variable	Area	Mean	Standard Deviation	Cases
temp	5	13.5	2.4	5
	6	14.3	1.9	9
	7	13.7	0.06	4
	8	13.7	0.00	1
cond	5	1.85	0.19	5
	6	1.92	0.18	9
	7	1.91	0.05	4
	8	1.95	0.00	1
pH	5	7.42	0.07	5
	6	7.25	0.08	9
	7	7.11	0.12	4
	8	7.00	0.00	1
D.O.	5	7.7	2.2	5
	6	6.9	1.4	9
	7	7.0	2.7	4
	8	6.6	0.0	1
alk	5	284	5.7	2
	6	307	32	4
	7	298	21	4
	8	309	1.4	2
CO_2	5	86	14	2
	6	105	21	4
	7	153	34	4
	8	157	16	2
Hard	5	299	26	2
	6	276	69	4
	7	263	36	3
	8	247	12	2

Table 12. Tukey Honestly Significant Difference test of mean pH for areas 5, 6, 7 and 8 of the Little Colorado River, April 1993, (** = significant differences).

pH by Area		Area	Area	Area	Area
Mean	Area	5	6	7	8
7.42	5				
7.25	6				
7.11	7	**			
7.00	8	**	**		

Table 13. Means of 7 water chemistry variables in areas 3, 4, 5, 6, 7, and 8 on the Little Colorado River, June 1993.

Variable	Area	Mean	Standard Deviation	Cases
temp	3	22.9	0.57	2
	4	23.1	0.14	2
	5	23.1	0.44	6
	6	23.4	0.47	12
	7	23.1	0.62	6
	8	22.7	1.1	6
cond	3	4.49	0.11	2
	4	3.85	1.01	2
	5	4.71	0.09	6
	6	4.77	0.04	12
	7	4.78	0.03	6
	8	4.77	0.10	6
pH	3	7.77	0.04	2
	4	7.68	0.01	2
	5	7.75	0.04	6
	6	7.79	0.04	12
	7	7.76	0.04	6
	8	7.57	0.03	6
D.O.	4	6.7	0.05	2
	5	5.9	0.82	6
	6	6.4	0.65	12
	7	6.5	0.44	6
	8	6.7	0.73	6
alk	5	601	42	5
	6	620	25	10
	7	605	47	5
	8	611	57	5
CO_2	3	101	12	5
	4	116	32	2
	5	150	18	5
	6	160	27	14
	7	175	31	10
	8	200	44	9
Hard	5	766	33	5
	6	785	45	10
	7	843	26	5
	8	820	20	5

*Dissolved oxygen not sampled in this area.

Table 14. Tukey Honestly Significant Differences test of mean a) conductivity, b) pH, and c) CO_2 for all areas of the Little Colorado River, June 1993, (** = significant differences).

a)

Cond by Area		Area	Area	Area	Area	Area	Area
Mean	Area	3	4	5	6	7	8
4.49	3		**				
3.85	4						
4.71	5		**				
4.77	6		**				
4.77	7		**				
4.78	8		**				

b)

pH by Area		Area	Area	Area	Area	Area	Area
Mean	Area	3	4	5	6	7	8
7.77	3		**				
7.68	4						
7.75	5						
7.79	6		**				
7.78	7		**				
7.57	8	**	**	**	**	**	

c)

CO_2 by Area		Area	Area	Area	Area	Area	Area
Mean	Area	3	4	5	6	7	8
101	3						
116	4						
150	5						
160	6	**					
175	7	**	**				
200	8	**	**				

(Table 14A). The mean pH for area 8 was significantly lower than those in areas 3, 4, 5, 6, and 7, while the mean for area 4 was significantly lower than the mean for area 6 and 7 (Table 14B). The mean CO_2 for area 3 was significantly lower than those for areas 6, 7, and 8, while CO_2 for area 4 was significantly lower than that in areas 7 and 8 (Table 14C). The mean hardness for area 5 was significantly lower than in area 7.

Variances of mean turbidity (Secchi disk) were not homogeneous (Bartlett-Box F statistic). The mean Secchi disk depth for area 7 (HSD analysis) was significantly higher than that in area 5 (Tables 7 and 15).

July 1993

There were significant differences (ANOVA) in conductivity, pH, dissolved oxygen, carbon dioxide and alkalinity among areas (Table 5, 16A, 16B, and 16C). However, the variance was not homogeneous (Bartlett-Box F test) among areas for pH and dissolved oxygen.

HSD analysis showed mean conductivity was significantly higher in area 15 than in all other areas; significantly lower in area 14 than in all other areas, except area 13; and significantly lower in area 13 than in all other areas, except area 14 (Table 17A).

HSD analysis showed mean dissolved oxygen for area 14 was significantly lower than those in all other areas

Table 15. ANOVA for turbidity measurements from several areas on the Little Colorado River, June 1993 and July 1993.

Month	Year	Variable	Sum of Squares Between	Sum of Squares Within	Mean Square Between	Mean Square Within	F	df B	df W	Signif.
Jun	93	Secchi	11.5	4.3	3.82	0.54	7.13	3	8	0.0120
Jul	93	NTU	12.9	0.81	4.29	0.10	42.3	3	8	0.0000

Table 16A. Means of 6 water chemistry variables in areas 5, 6, 7, and 8, on the Little Colorado River, July 1993.

Variable	Area	Mean	Standard Deviation	Cases
temp	5	23.5	1.9	5
	6	23.2	1.5	6
	7	23.9	2.0	5
	8	23.8	1.9	5
cond	5	4.75	0.04	5
	6	4.70	0.09	6
	7	4.69	0.08	5
	8	4.69	0.08	5
pH	5	7.78	0.07	5
	6	7.83	0.06	6
	7	7.73	0.06	5
	8	7.52	0.03	5
D.O.	5	7.5	0.35	5
	6	7.6	0.42	6
	7	7.8	0.34	5
	8	8.2	1.3	5
alk	5	624	56	2
	6	661	13	2
	7	649	4.2	2
	8	625	8.5	2
CO_2	5	159	16	11
	6	156	9.5	12
	7	175	21	11
	8	191	19	11

Table 16B. Means of 6 water chemistry variables in areas 2, 3, 4, and 9, on the Little Colorado River, July 1993.

Variable	Area	Mean	Standard Deviation	Cases
temp	2	22.5	1.0	4
	3	23.8	0.24	4
	4	24.1	0.21	2
	9	20.7	0.21	2
cond	2	4.57	0.06	4
	3	4.66	0.04	4
	4	4.75	0.05	2
	9	4.76	0.09	2
pH	2	7.82	0.02	4
	3	7.76	0.08	4
	4	7.61	0.06	2
	9	7.34	0.01	2
D.O.	2	7.6	0.51	4
	3	7.7	0.41	4
	4	7.1	0.71	2
	9	7.2	0.28	2
alk	2	573	6.6	4
	3	*		
	4	598	21	2
	9	*		
CO_2	2	115	19	8
	3	117	14	7
	4	143	12	4
	9	193	15	3

*No samples taken for variable in this area.

Table 16C. Means of 5 water chemistry variables in areas 12, 13, 14, and 15, on the Little Colorado River, July 1993.

Variable	Area	Mean	Standard Deviation	Cases
temp	12	23.5	2.12	2
	13	27.5	6.65	2
	14	21.3	0.00	1
	15	22.6	0.00	1
cond	12	4.62	0.05	2
	13	4.20	0.02	2
	14	4.15	0.00	1
	15	6.08	0.00	1
pH	12	6.89	0.04	2
	13	6.76	0.21	2
	14	6.36	0.00	1
	15	6.87	0.00	1
D.O.	12	9.1	3.11	2
	13	7.3	0.42	2
	14	4.0	0.00	1
	15	7.3	0.00	1
CO_2	12	205	12	3
	13	255	55	3
	14	571	26	3
	15	172	17	3

Table 17. Tukey Honestly Significant Differences test of mean a) conductivity and b) dissolved oxygen for all areas of the Little Colorado River, July 1993, (* = significant differences).

a)

Cond by Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area
Mean		2	3	4	5	6	7	8	9	12	13	14	15
4.57	2												
4.66	3												
4.75	4												
4.75	5												
4.7	6												
4.69	7												
4.69	8												
4.76	9												
4.62	12												
4.20	13	*	*	*	*	*	*	*	*	*			
4.15	14	*	*	*	*	*	*	*	*	*			
6.06	15	*	*	*	*	*	*	*	*	*	*	*	

b)

D.O. by Area	Ares	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area
Mean		2	3	4	5	6	7	8	9	12	13	14	15
7.6	2												
7.7	3												
7.1	4												
7.5	5												
7.6	6												
7.8	7												
8.2	8												
7.2	9												
9.1	12												
7.3	13												
4.0	14	*	*	*	*	*	*	*	*	*	*		*
7.3	15												

Table 17. Tukey Honestly Significant Difference test of mean c) pH and d) carbon dioxide for all areas on the Little Colorado River, July 1993, (* = significant differences).

c)

pH by Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area
Mean		2	3	4	5	6	7	8	9	12	13	14	15
7.82	2												
7.76	3												
7.61	4												
7.78	5												
7.82	6												
7.73	7												
7.52	8	*	*		*	*							
7.34	9	*	*	*	*	*	*						
6.89	12	*	*	*	*	*	*	*	*				
6.76	13	*	*	*	*	*	*	*	*				
6.36	14	*	*	*	*	*	*	*	*	*	*		*
6.87	15	*	*	*	*	*	*	*	*				

d)

CO_2 by Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area	Area
Mean		2	3	4	5	6	7	8	9	12	13	14	15
115	2												
117	3												
143	4												
159	5	*											
156	6												
175	7	*	*										
191	8	*	*	*									
193	9	*	*	*									
205	12	*	*	*	*	*							
255	13	*	*	*	*	*	*	*	*	*			
570	14	*	*	*	*	*	*	*	*	*	*		
172	15	*	*								*	*	

sampled (Table 17B). Mean pH increased significantly downstream (Table 17C), carbon dioxide decreased significantly downstream (Table 17D), and mean alkalinity for area 6 was significantly higher than that in area 2.

Mean turbidity (NTU) was significantly different (Table 15) among areas (Tables 7 and 18). The mean for area 8 was significantly lower (HSD analysis) than those in areas 5, 6, and 7. The mean for area 7 was significantly lower than those in areas 5 and 6.

Macrohabitat

Macrohabitat conditions varied over time at study areas on the LCR (Tables 19, 20, 21, 22, Figures 3-6).

In July 1992 area 7 averaged 44.2 m wide, 57 cm deep, and had a modal velocity of 2 (0.10-0.30 m/s) and substrate of 2 (sand). Area 8 averaged 45.7 m wide, 60 cm deep, and had a modal velocity of 2 (0.10-0.30 m/s) and substrate of 2 (sand). Area 9 averaged 35.5 m wide, 56 cm deep, and had a modal velocity of 3 (0.30-0.70 m/s) and a modal substrate of 2 (sand).

In August 1992 area 7 averaged 58.2 m wide, 67 cm deep, and had a modal velocity of 3 (0.30-0.70 m/s) and a modal substrate of 2 (sand). Area 8 averaged 39.3 m wide, 123 cm deep, and had a modal velocity of 2 (0.10-0.30 m/s) and substrate of 2 (sand).

In September 1992 area 7 averaged 36.4 m wide, 68 cm deep, and had a modal velocity of 3 (0.30-0.70 m/s) and a

Table 18. Mean turbidity readings (NTU) and associated standard deviations for several areas on the Little Colorado River, July 1993.

Area	Mean	Std. dev.	Cases
5	4.00	0.50	3
6	3.53	0.15	3
7	2.40	0.36	3
8	1.33	0.06	3

Table 19. Average width of several areas on the Little Colorado River, 1992-1993.

Month	Year	Area	Average Width	Num. of Transects
July	1992	7	44.21	4
		8	45.73	4
		9	35.53	4
August	1992	7	58.21	7
		8	39.32	1
September	1992	7	36.37	4
		9	47.09	4
		12	30.10	1
		14	21.13	1
April	1993	5	33.10	2
June	1993	5	26.97	2
		6	28.74	3
		7	39.77	3
		8	55.60	2

Table 20. Depth (means) from several areas on the Little Colorado River, 1992-1993.

Month	Year	Area	Mean	Cases
July	1992	7	57	182
		8	60	199
		9	56	148
August	1992	7	67	374
		8	123	73
September	1992	7	68	149
		9	60	188
		12	87	31
		14	66	25
April	1993	5	142	68
June	1993	5	87	56
		6	104	113
		7	126	99
		8	69	113

Table 21. Velocity (means and modes) for several areas on the Little Colorado River, 1992-1993.

Month	Year	Area	Mean	Mode	Cases
July	1992	7	2.7	2	182
		8	2.7	2	199
		9	2.6	3	148
August	1992	7	3.0	3	374
		8	2.9	2	73
September	1992	7	2.9	3	149
		9	3.3	3	188
		12	2.9	3	31
		14	2.4	3	25
April	1993	5	2.2	3	68
June	1993	5	1.8	2	56
		6	1.8	2	113
		7	2.5	1	99
		8	2.4	1	113

Table 22. Substrate (means and modes) for several areas on the Little Colorado River, 1992-1993.

Month	Year	Area	Mean	Mode	Cases
July	1992	7	4.1	2	182
		8	3.6	2	199
		9	2.5	2	148
August	1992	7	4.1	2	371
		8	4.0	2	73
September	1992	7	2.4	1	149
		9	4.1	2	188
		12	2.6	2	31
		14	3.7	2	25
April	1993	5	4.9	2	65
June	1993	5	2.3	1	56
		6	2.8	1	113
		7	4.7	2	97
		8	4.1	2	113

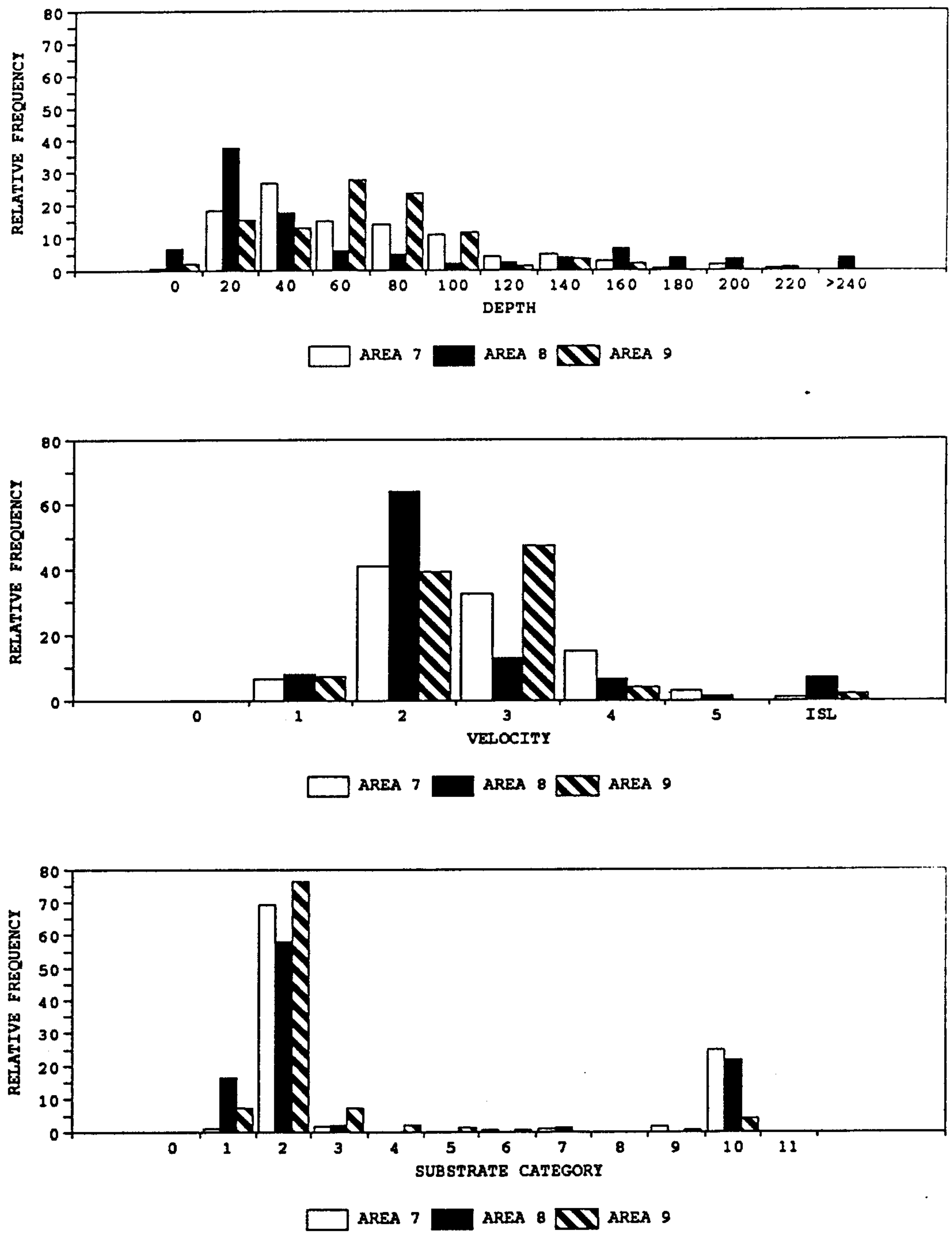


Figure 3. Relative frequency histograms of depth, velocity, and substrate for several areas of the Little Colorado River, July 1992.

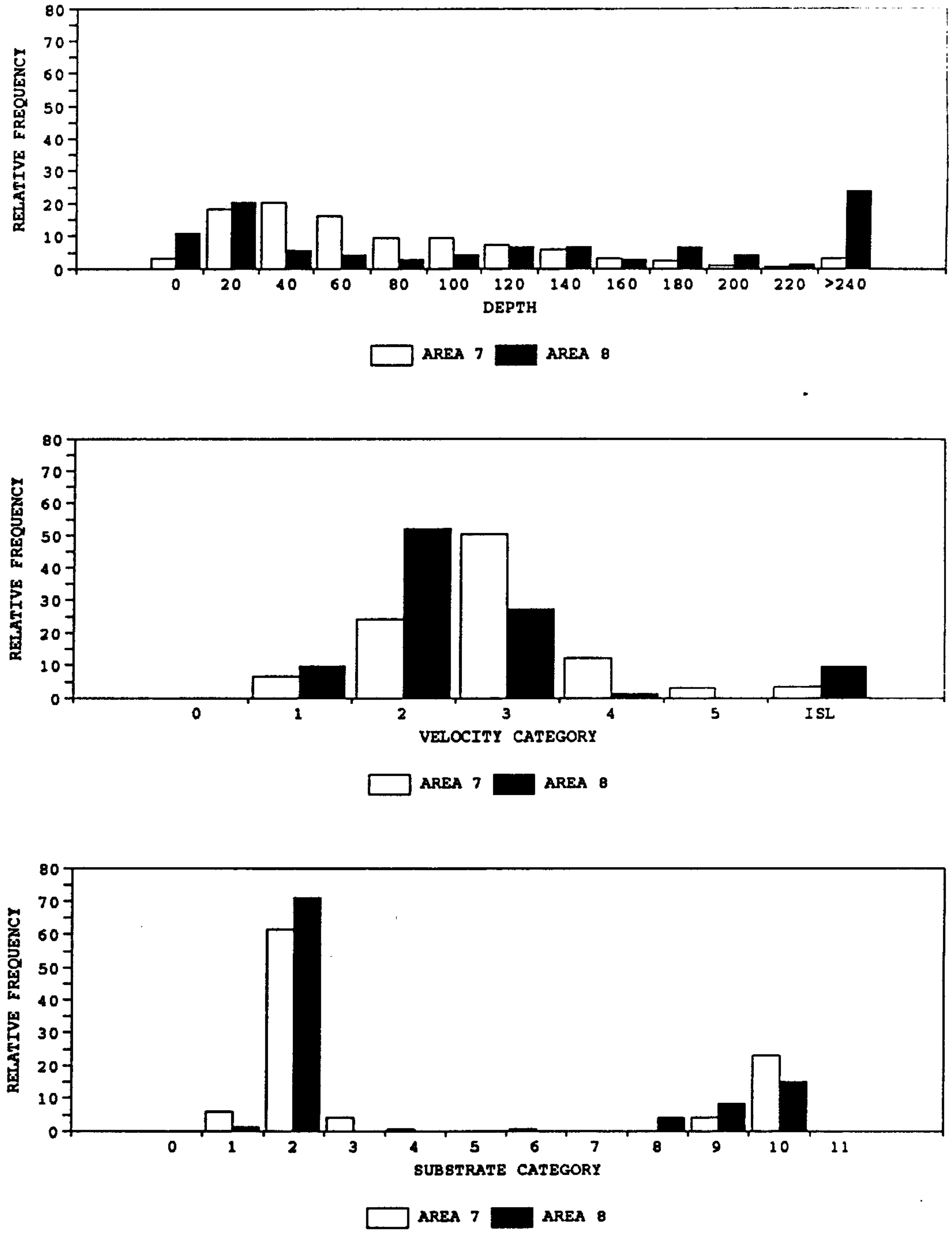


Figure 4. Relative frequency histograms of depth, velocity, and substrate for several areas of the Little Colorado River, August 1992.

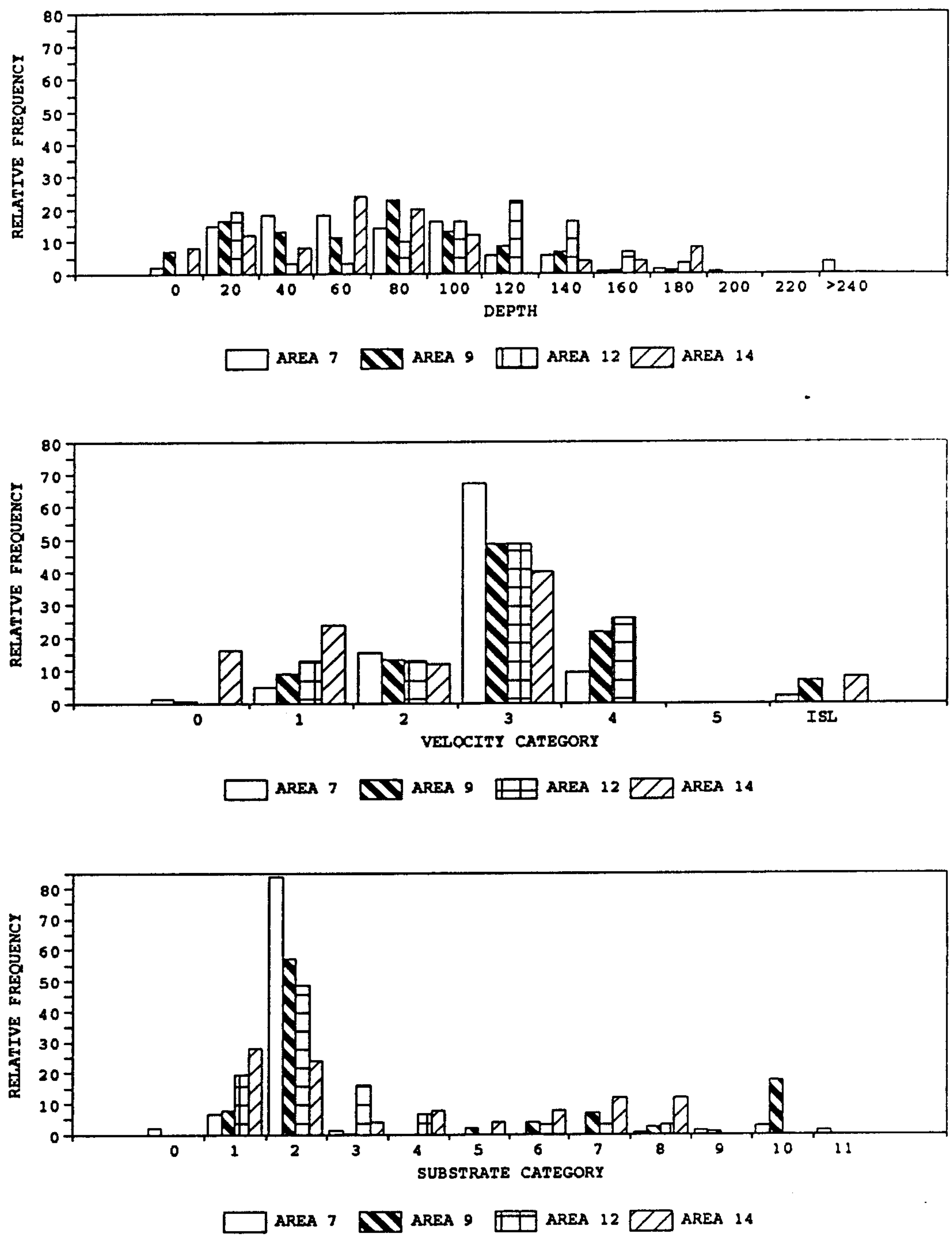


Figure 5. Relative frequency histograms of depth, velocity, and substrate for several areas of the Little Colorado River, September 1992.

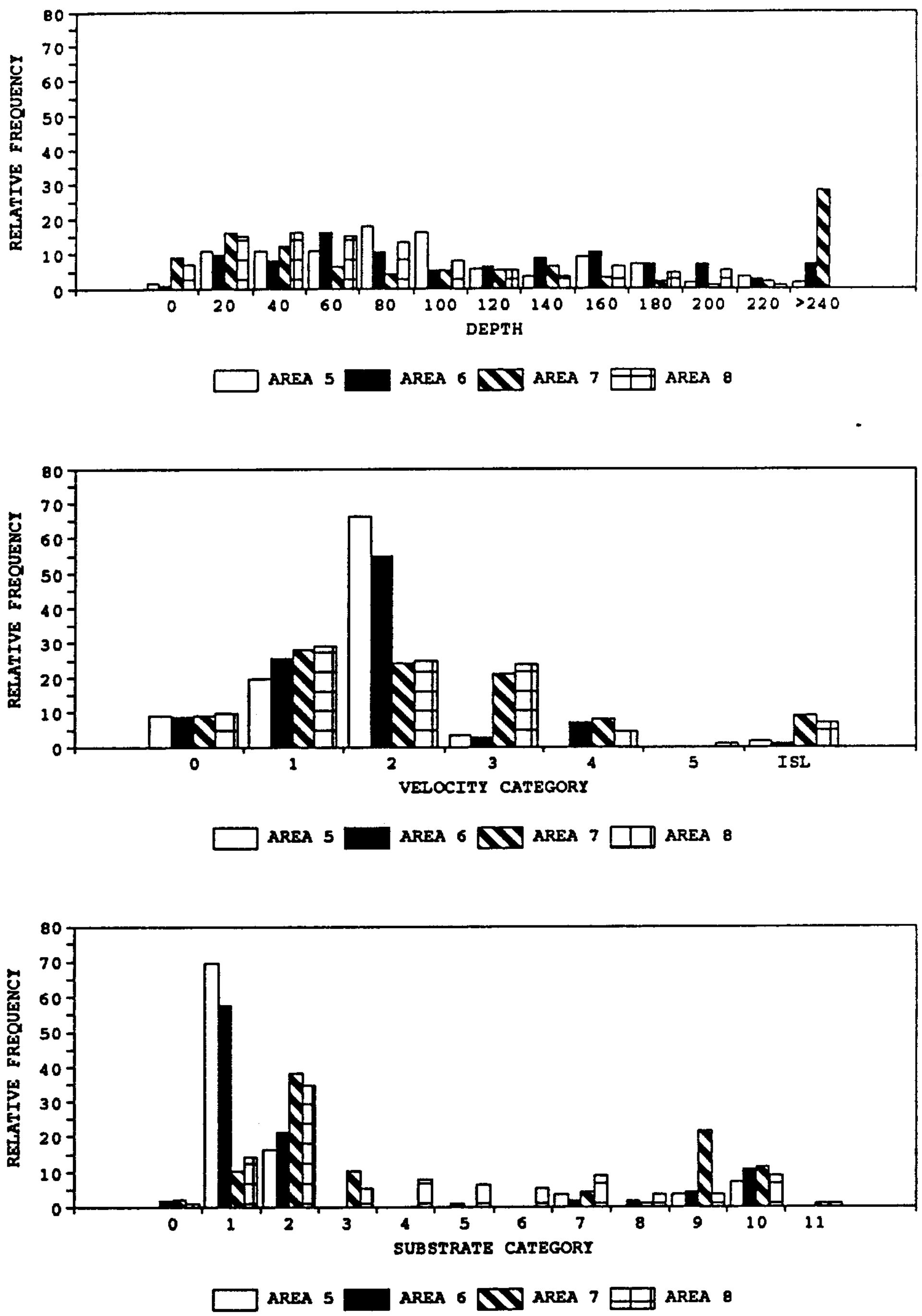


Figure 6. Relative frequency histograms of depth, velocity, and substrate for several areas of the Little Colorado River, June 1993.

modal substrate of 1 (silty-sand). Area 9 averaged 47.1 m wide, 60 cm deep, and had a modal velocity of 3 (0.30-0.70 m/s) and a modal substrate of 2 (sand). Area 12 averaged 30.1 m wide, 87 cm deep, and had a modal velocity of 3 (0.30-0.70 m/s) and a modal substrate of 2 (sand). Area 14 averaged 21.1 m wide, 66 cm deep, and had a modal velocity of 3 (0.30-0.70 m/s) and a modal substrate of 2 (sand).

In April 1993 area 5 averaged 33.1 m wide, 142 cm deep, and had a modal velocity of 3 (0.30-0.70 m/s) and a modal substrate of 2 (sand).

In June 1993 area 5 averaged 27.0 m wide, 87 cm deep and had a modal velocity of 2 (0.10-0.30 m/s) and a modal substrate of 1 (silty-sand). Area 6 averaged 28.7 m wide, 104 cm deep, and had a modal velocity of 2 (0.10-0.30 m/s) and a modal substrate of 1 (silty-sand). Area 7 averaged 39.8 m wide, 126 cm deep, and had a modal velocity of 1 (0.02-0.10 m/s) and a modal substrate of 2 (sand). Area 8 averaged 55.6 wide, 69 cm deep, and had a modal velocity of 1 (0.02-0.10 m/s) and a modal substrate of 2 (sand).

Kolmogorov-Smirnov two-sample testing of the June 1993 data showed significant differences in the cumulative distributions of depth, velocity, and substrate between several of the areas tested (Table 23). There were significant differences in the cumulative distributions of depth for areas 6 vs 7, 6 vs 8, and 7 vs 8. Generally, area 7 was much deeper than areas 6 and 8; and area 6 was deeper

Table 23. Results of Kolmogorov-Smirnov 2-Sample Test for physical parameters from several areas on the Little Colorado River, June 1993.

VARIABLE	AREAS COMPARED	CASES	MOST EXTREME DIFFERENCES			K-S Z	P
			ABSOLUTE	POSITIVE	NEGATIVE		
DEPTH	5,6	56,113	0.184	0.059	-0.184	1.12	0.16
	5,7	56,99	0.273	0.155	-0.273	1.63	0.01
	5,8	56,113	0.218	0.218	-0.008	1.34	0.06
	6,7	113,99	0.264	0.264	-0.198	1.92	0.001
	6,8	113,113	0.248	0.00	-0.248	1.86	0.002
	7,8	99,113	0.304	0.304	-0.047	2.21	0.00
VELOCITY	5,6	56,113	0.062	0.059	-0.062	0.38	1.00
	5,7	56,99	0.330	0.088	-0.330	1.98	0.001
	5,8	56,113	0.309	0.104	-0.309	1.89	0.002
	6,7	113,99	0.278	0.278	-0.029	2.02	0.001
	6,8	113,113	0.257	0.257	-0.044	1.93	0.001
	7,8	99,113	0.048	0.048	0.00	0.35	1.00
SUBSTRATE	5,6	56,113	0.104	0.018	-0.104	0.63	0.82
	5,7	56,97	0.573	0.021	-0.573	3.41	0.00
	5,8	56,113	0.546	0.009	-0.546	3.34	0.00
	6,7	113,97	0.469	0.469	-0.003	3.39	0.00
	6,8	113,113	0.443	0.443	-0.018	3.32	0.00
	7,8	97,113	0.208	0.208	-0.060	1.50	0.02

than area 8. There were significant differences in the cumulative distributions of velocity for areas 6 vs 7, 6 vs 8, 5 vs 7, and 5 vs 8. Generally, areas 5 and 6 had slower velocities than 7 and 8. There were significant differences in the cumulative distributions of substrate for areas 6 vs 7, 6 vs 8, 5 vs 7, and 5 vs 8. Generally, areas 5 and 6 had smaller substrates than areas 7 and 8. This is a result of the large amount of $CaCO_3$ precipitate (marl).

Microhabitat and Fish Capture

Speckled dace were found in all areas sampled except directly in Blue Springs and in the main channel downstream of Blue Springs for about 1 km. They were the only native fish that occurred above area 7 (Tables 24-30). Humpback chub were found only in areas 1, 2, 6, and 7. Flannelmouth sucker were found in areas 2, 5 and 7. Juvenile bluehead sucker were observed only in area 2. Exotic species encountered included fathead minnow, carp, and channel catfish. Fathead minnow were found in areas 6 and 7, carp in areas 2, 7, and 9, and channel catfish in area 7.

Length frequency histograms for speckled dace are presented in Appendix A (Figures 7-10). Catch per unit effort for speckled dace and the total number of nets fished in each area by month are given in Appendix A (Figure 11, Table 31). Observational data on 241 juvenile speckled dace in June 1993 indicated that 14 (6%) were located in the top

Table 24. Sample methods used for fish capture (mini-hoop net [HN], minnow trap [TR], underwater observation [SK], visual observation [VO]), and areas sampled per trip the Little Colorado River.

Month	Year	Areas sampled	Gear Used
July	1992	7,8,9	HN, TR
August	1992	7	HN
September	1992	7,9,10,11,12,14	HN
April	1993	5,6,7,8	HN, TR
June	1993	6,7,8	HN, TR, SK
July	1993	1,2,5,6,7,9,12,13,14,15	SK, VO

Table 25. Fish capture data for several areas on the Little Colorado River, July 1992.

Area	Species	Number Captured	Gear Used
7	G. cypha	5	HN
7	R. osculus	109	HN
7	R. osculus	3	MT
8	R. osculus	107	HN
9	R. osculus	76	HN

Table 26. Fish capture data for several areas on the Little Colorado River, August 1992.

Area	Species	Number Captured	Gear Used
7	G. cypha	2	HN
7	R. osculus	125	HN
7	P. promelus	5	HN
7	I. punctatus	1	HN

Table 27. Fish capture data for several areas on the Little Colorado River, September 1992.

Area	Species	Number Captured	Gear Used
7	G. cypha	1	HN
7	R. osculus	44	HN
7	I. punctatus	3	HN
7	C. caprio	12	HN
9	R. osculus	212	HN
9	C. caprio	1	HN
10	R. osculus	23	HN
11	R. osculus	3	HN
12	R. osculus	12	HN
14	No fish		HN

Table 28. Fish capture data for several areas on the Little Colorado River, April 1993.

Area	Species	Number Captured	Gear Used
5	R. osculus	18	HN
5	R. osculus	2	TR
5	C. latipinnis	1	HN
6	G. cypha	1	HN
6	R. osculus	78	HN
6	R. osculus	59	TR
7	R. osculus	358	HN
7	C. latipinnis	1	HN
7	R. osculus	292	TR
8	R. osculus	550	HN

Table 29. Fish capture data for several areas on the Little Colorado River, June 1993.

Area	Species	Number Captured	Gear Used
6	R. osculus	729	VO
6	P. promelus	1	HN
6	R. osculus	753	SK
6	R. osculus	15	VO
7	R. osculus	1328	VO
7	R. osculus	395	SK
8	R. osculus	723	VO
8	R. osculus	43	SK
8	R. osculus	100	VO

Table 30. Fish capture data for several areas on the Little Colorado River, July 1993.

Area	Species	Number Captured	Gear Used
1	G. cypha	3	VO
1	R. osculus	30	VO
2	G. cypha	270*	SK
2	C. latipinnis	2	SK
2	P. discobolus	134	SK
2	R. osculus	249	SK
2	C. caprio	4	SK
5	R. osculus	20	VO
6	R. osculus	100	VO
7	R. osculus	150	SK
9	R. osculus	150	VO
12	R. osculus	150	SK
13	No fish Captured		
14	R. osculus	11**	VO
15	R. osculus	150	VO

*3 G. cypha were adults (length >150 mm.).
**1 R. osculus was floating in the Blue Springs water and 10 were in a side pool where the water quality was different from Blue Springs.

third of the water column, 86 (36%) were located in the middle third of the water column, and 141 (58%) were located in the bottom third of the water column.

The relative frequencies of habitat conditions (depth, velocity, substrate) sampled versus used by speckled dace are presented in Appendix B (Figures 12-29). The Kolmogorov-Smirnov two-sample test indicated that there were no differences in the distribution of habitat conditions sampled versus the distribution of conditions used by speckled dace.

DISCUSSION

Overview

There was a distinct longitudinal pattern in fish distribution in the lower 21 kilometer of the Little Colorado River. The pattern was especially dramatic with regards to humpback chub in the area from above Chute Falls (>14.6 km) to below Atomizer Falls (<14 km) and with speckled dace in the area of Blue Springs (21 km). Humpback chub distribution during base flow was correlated with water chemistry conditions (principly carbon dioxide and calcium carbonate levels) and physical habitat conditions (principly turbidity, and presence or absence of travertine and deep pools). Distribution of speckled dace during base flow was correlated with water quality factors (principly carbon dioxide and calcium carbonate levels).

The characteristics of water from Blue Springs dominate the chemical composition of the lower 21 km of the LCR when it is at or near base flow. The chemical composition of the water from Blue Springs is influenced by the soils it passes through prior to its emergence, resulting in elevated carbon dioxide and calcium bicarbonate levels. Upon emergence the water is altered through carbon dioxide and calcite equilibrium processes which translate into a gradual change in water chemistry downstream of Blue Springs.

CO_2 and $Ca(HCO_3)_2$ in Water From Blue Springs.

Water above Blue Springs descends through soils and becomes acidic. This occurs when the water becomes charged with the products of decomposition in organic soils (Hem 1970, Cole 1983), or other processes occur to lower the pH. If organic soil is present carbon dioxide in the soil is absorbed to supersaturation levels (Cole 1983) because it is highly soluble in water, even more so than oxygen (Cole 1983). Once dissolved in water, the CO_2 exists as carbon dioxide (CO_2), carbonic acid (H_2CO_3), bicarbonate ions (HCO_3^-), and carbonate ions ($CO_3^{=}$). The dissociation of CO_2 in water is depicted by the following equations (Cole 1983, Moyle 1988, Pankow 1991);

$$CO_2 + H_2O \longleftrightarrow H_2CO_3 \longleftrightarrow HCO_3^- + H^+ \longleftrightarrow CO_3^{=} + H^+ \quad (1)$$

The forms which are present in equation 1 are dependent on the pH of the water (Stumm and Morgan 1970, Post 1979, Cole 1983).

The water of Blue Springs is supersaturated with calcium bicarbonate (Cole and Kubly 1976, Cole 1975, Hem 1970). The supersaturation of the water with calcium bicarbonate occurs when water of low pH contacts soils rich in calcium carbonate. In the case of Blue Spring these soils are present in deeply buried caverns of limestone (Hem 1970). Acidic water causes calcium carbonate within the sediments to go into solution as calcium bicarbonate leading to the high levels of alkalinity (as HCO_3^-) and calcium hardness (HACH 1989), which is characteristic of the LCR during base flow.

Equilibrium Processes of Water From Blue Springs

The longitudinal gradients of carbon dioxide, pH, alkalinity, and hardness in the LCR are controlled by the carbon dioxide concentration (see Hem 1970, Stumm and Morgan 1970, Cole 1983). The changing levels are due to the equilibrium processes of CO_2 and $Ca(HCO_3)_2$ in the water (Cole 1983). Equilibrium is reached gradually as carbon dioxide is lost to the atmosphere (Stumm and Morgan 1970), or consumed through chemical reactions (i.e., precipitation of travertine and photosynthesis) (Stumm and Morgan 1970, Cole 1975). Calcite equilibrium (pH_s) is defined as the calculated pH at which water is in equilibrium with solid calcium carbonate (Standard Methods 1965). At equilibrium there is no further change in total alkalinity, calcium, or carbon dioxide levels. In the LCR, CO_2, Ca^{++} (as measured by hardness) and HCO_3^- (as measured by alkalinity) levels decreased, while pH and turbidity levels increased downstream from 21.06 km to 11.40 km (Tables 13A-B, 16A-C, and 18). The most abrupt changes occur in pH, carbon dioxide, hardness and turbidity between 14.7 km (just above Chute Falls) and 13.94 km (just below Atomizer Falls); a distance of 760 m. Other studies on the LCR report similar findings (Hem 1970, Cole 1975, Cole and Kubly 1976, Keading and Zimmerman 1983, Angradi et al. 1992, AGF 1993). Equilibrium is not attained in this reach (14.7 km to 13.9 km) of the LCR, however, it is apparent that equilibrium processes change the levels of CO_2 and HCO_3^-. Both factors are physiologically limiting to fishes at high levels.

Fish Distribution

The changes in the levels of CO_2 and HCO_3^- downstream from Blue Springs correlate with changes in fish distribution. Speckled dace do not occur in Blue Springs (21 km) (Carothers and Aitchison 1971, Carothers and Minckley 1983), where CO_2 is 571 mg/l and water temperature is 22.6° C, but occur downstream (19 km) where CO_2 is 205 mg/l and water temperature is 23.5° C, and occur upstream (21.06 km) where CO_2 is 172 mg/l and water temperature is 22.6° C. Humpback chub do not occur above Chute Falls (14.7 km, 196 mg/l CO_2, 618 mg/l alkalinity, 23.3° C water temperature), but do occur in low densities below Chute Falls (14.3 km to 14.5 km, 175 mg/l CO_2, 627 mg/l alkalinity, 23.5° C water temperature), and in larger numbers below Atomizer Falls (13.9 km, 158 mg/l CO_2, 613 mg/l alkalinity, 23.3° C water temperature). They are abundant below Mecca Falls (11.4 km to 12.6 km, 111 mg/l CO_2, 573 mg/l alkalinity, 23.1° C water temperature).

Fish Physiology As It Relates To CO_2 and HCO_3^-

The elevated levels of CO_2 and HCO_3^- present in the LCR may physiologically limit the distribution of fishes. In waters, like Blue Springs, where extremely high levels of CO_2 and HCO_3^- occur, the diffusion of CO_2 and the active exchange of HCO_3^- across the gill tissues is blocked in fish by the high gradients of CO_2 and HCO_3^- in the environment (Post 1979, Claiborne and Heisler 1984). This blockage can lead to anesthesia (Shelford and Allee 1912, Powers 1937, Fish 1943, Fry et al. 1947, Basu 1959, Dahlberg et al. 1968, Eddy et al. 1977, Mishra and Mishra 1983) and death of fishes (Black et al. 1954, Alabaster 1957, Booke et al. 1978, Post 1979, Yoshikawa et al. 1991), by causing metabolic wastes to concentrate. This changes the ratio of oxygen to carbon dioxide in the brain and produces anoxia (Post 1979). The LCR is high in sodium chloride (Cole 1975). This could add to the stress of the fish when there are high levels of environmental CO_2 and HCO_3^- (Moyle 1988).

Anesthesia has been documented in speckled dace exposed to Blue Springs water (Carothers and Aitchison 1977). Carothers and Aitchison (1977) placed dace from above and below Blue Springs in water emanating directly from the spring. Fish from above the springs swam erratically around the container, gulped air at the surface, and became completely anesthetized within 3 minutes. Fish from below the springs either had no reaction or had a short initial reaction followed by full recovery.

The reaction of speckled dace from above Blue Springs is similar to that described for species of salmon (*Oncorhynchus tschawytscha*) and steelhead trout (*Oncorhynchus mykiss*) subjected to 200 ppm CO_2 (@-11.4° C= 80.6 mm Hg) (Fish 1943). It may be that the high levels of CO_2 (571 mg/l) emanating from Blue Spring preclude dace from surviving directly in the spring and in the main river channel downstream to 19 km.

Acclimation would explain the discrepancy in the reactions of the 2 groups of dace in the Carothers and Aitchison (1977) study. Fish can acclimate somewhat to elevated levels of CO_2 and HCO_3^-. Sustained hypercapnia (elevated CO_2 levels) causes the concentration of plasma CO_2 and HCO_3^- to increase and plasma pH to decrease (Claiborne and Heisler 1984), but fish can regulate their internal pH via HCO_3^-/Cl^- exchange across the gills (Janssen and Randall

1975, Claiborne and Heisler 1984).

There are no studies on the CO_2 tolerance limits for humpback chub or other native fishes of the Grand Canyon. However, it appears reasonable to hypothesize that high CO_2 levels block the entrance of humpback chub into the upper parts of the LCR. The lethal limit of CO_2 for the common white sucker (*Catostomus commersonnii commersonnii*) is 260 mg/l at 17.1° C and an average weight of 265 g, and that for the northern fathead minnow (*P. promelas promelas*) is 293 mg/l CO_2 at 20.4° C and an average weight of 50 g (Black et al. 1954). Yoshikawa et al. (1991) found the minimum environmental CO_2 required for anesthesia of carp (each weighing approximately 500 grams) to be between 100 and 125 mm Hg at 23° C (238 and 298 mg/l CO_2). The lethal level of CO_2 varies with species and acclimation levels of oxygen, temperature and carbon dioxide (Powers 1937, Black et al. 1954, Alabaster 1957, Takeda and Itazawa 1983).

Although it appears reasonable from the forgoing discussion to hypothesize that chemical conditions during periods of base flow blocked access of humpback chub into the upper parts of the LCR, there are also physical habitat conditions that varied longitudinally. The most important of these factors from the standpoint of humpback chub appears to be decreased turbidity as one moves upstream and the absence of travertine deposits and deep pools above the

Atomizer Falls complex. Recent studies of the habitat preferences of humpback chub indicate that they use turbidity as cover (Valdez et al. 1992) and occupy reaches of the river characterized by deep swift water which has eddies associated with bedrock, boulder, and sand substrates (Holden and Stalnaker 1975, Holden 1978, Behnke and Benson 1980, Valdez and Nilson 1982, Keading et al. 1990, Valdez 1991). In the LCR humpback chub appear most abundant in those areas where turbidity is high and travertine dams form deep pools; they are absent where turbidity is low and travertine dams are scarce (Tables 25-30). Therefore, the clear water and the lack of the travertine dam complexes and deep pools upstream of Chute Falls, makes it impossible to entirely discount these factors as contributing to the absence of humpback chub from the upper part of the LCR.

The physical characteristics of the LCR appear to be in a constant state of flux. There is indication that travertine dams have been breached and formed over many years and that habitat conditions have changed frequently as a consequence. In fact, the habitat conditions in the LCR are still very dynamic. Floods in 1993 deposited large amounts of sand on the river banks while they scoured sand and marl ($CaCO_3$) out of pools, thus increasing the average depth of the river at base flow. If habitat conditions were controlling the distribution of humpback chub, one would expect that the distribution would have changed periodically. Since there is limited historical information on the distribution of humpback chub in the LCR it is impossible to evaluate this hypothesis.

None of the habitat factors discussed above as being important for humpback chub are important to speckled dace. Therefore, the absence of speckled dace from the area in and immediately below Blue Springs appears solely related to water chemistry conditions.

The high levels of CO_2 in the waters from Blue Springs may form a barrier to fish distribution during periods of base flow but would not form such a barrier during high flow periods. Blue Springs water is diluted during flood events (Cole and Kubly 1976). During such periods, there were high variances and limited patterning in the water chemistry data. However, high CO_2 levels could still block access of chub to the upper part of the LCR if floods occurred during periods of low temperatures. AGF (1993) found high CO_2 levels during periods of high flow and cold temperatures.

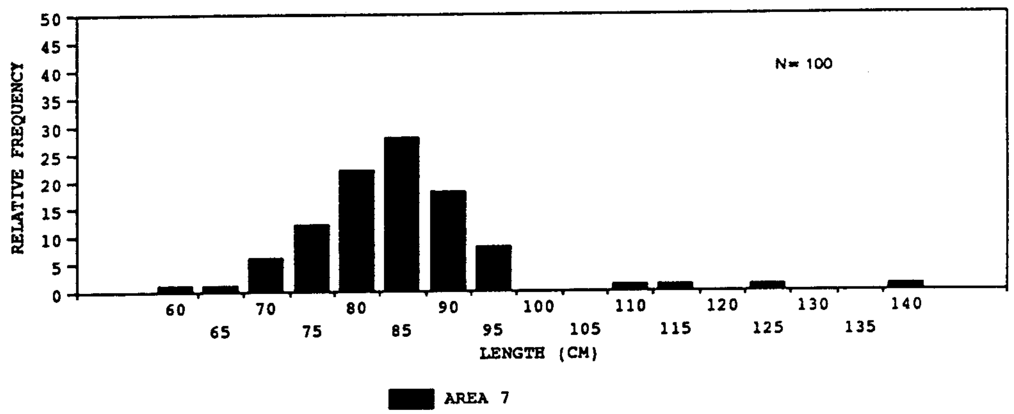
It is possible that the timing of the humpback chub movement into the LCR for spawning may play a role in their absence from the upper parts of the LCR. Humpback chub begin to move upstream in the LCR in April prior to spawning (Keading and Zimmerman 1983, Maddux et al. 1987, Kubly 1990). At this time the river is often swollen with the waters from snowmelt. Fish appear to migrate slowly up the river over the spawning period, often arriving at the Atomizer Falls complex during base flow periods in June and July (personal observation). The slow movement is consistent with gradual acclimation to high levels of CO_2 (Janssen and Randall 1975, Eddy et al. 1977, Claiborne and Heisler 1984). By the time humpback chub reach the Atomizer Falls complex the chemical barrier formed by the waters from Blue Springs at base flow is present and may block further upstream movement.

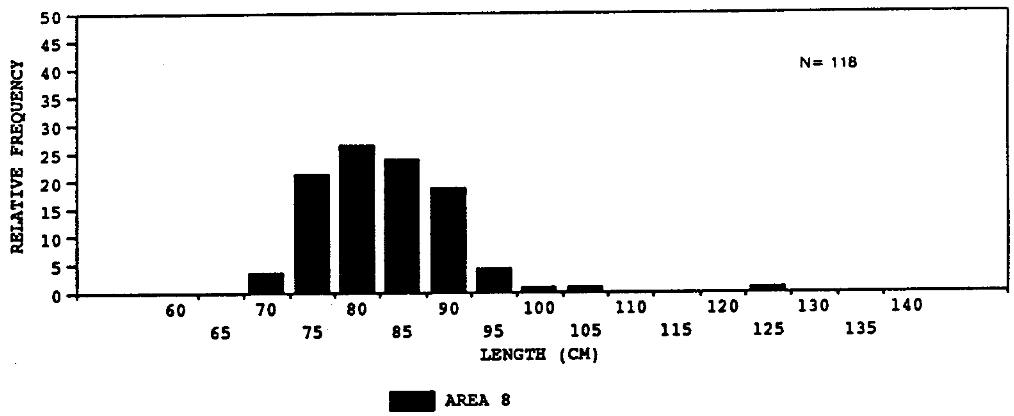
One might legitimately ask why humpback chub do not bypass Blue Springs during summer flood flows. The duration of summer floods are often short. The limited duration of flood flows may not allow sufficient time for fish to navigate the 7 kilometers between the Atomizer Falls complex and Blue Springs. This hypothesis is strengthened by the fact that chub have not penetrated further upstream than Chute Falls in recent years (Carothers and Minckley 1980, Keading and Zimmerman 1983), but chub, as well as squawfish (*Ptychocheilus lucius*), have been reported from just below Grand Falls prior to the 1940's (Miller 1963). Hereford (1984) has hypothesized that average annual discharge was higher in the LCR prior to 1940. Higher discharges may have diluted Blue Springs for long periods during the warm summer months prior to 1940 and allowed fish to move upstream.

RECOMMENDATIONS

I recommend that studies be done on the carbon dioxide tolerances of various size classes of humpback chub, and at various acclimation conditions for temperatures, dissolved oxygen, and carbon dioxide. I also recommend that these same studies be done on other species native to the lower 21 km of the LCR. These studies should either substantiate or falsify my hypotheses.

APPENDIX A: SPECKLED DACE; LENGTH FREQUENCY, CATCH PER UNIT EFFORT, AND TOTAL NETS FISHED FOR SEVERAL AREAS ON THE LITTLE COLORADO RIVER.





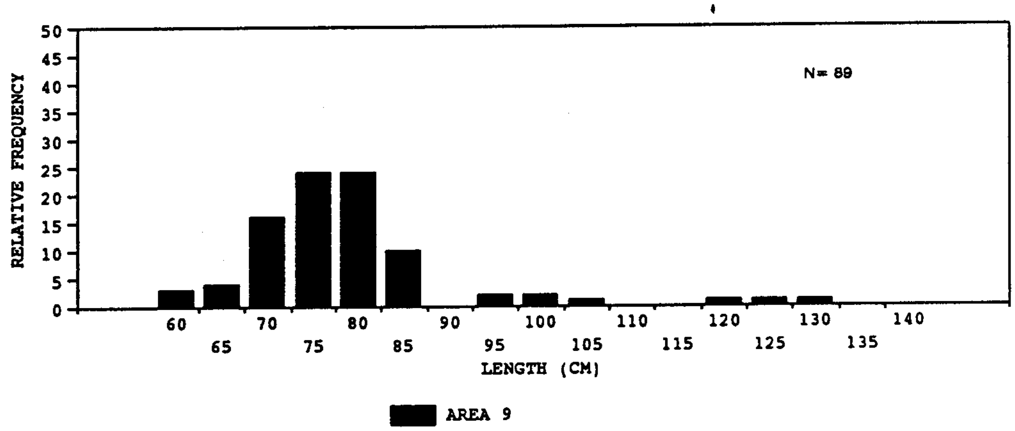
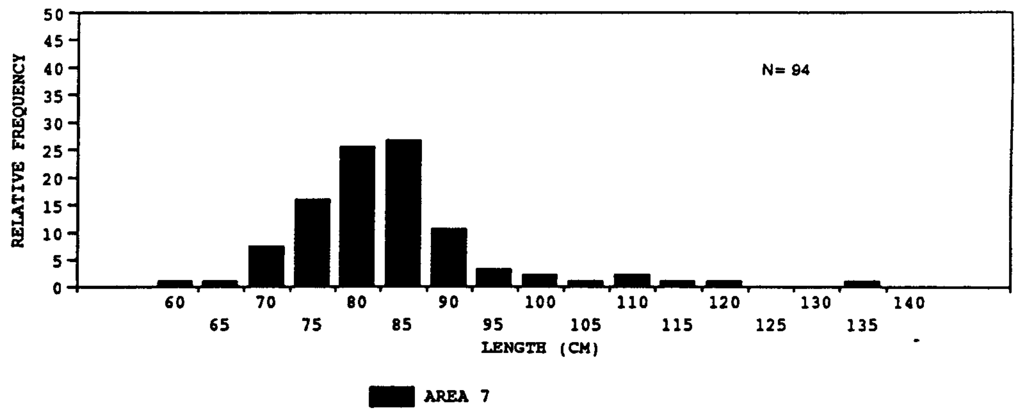


Figure 7. Length frequency distribution of speckled dace in several areas of the Little Colorado River, July 1992.



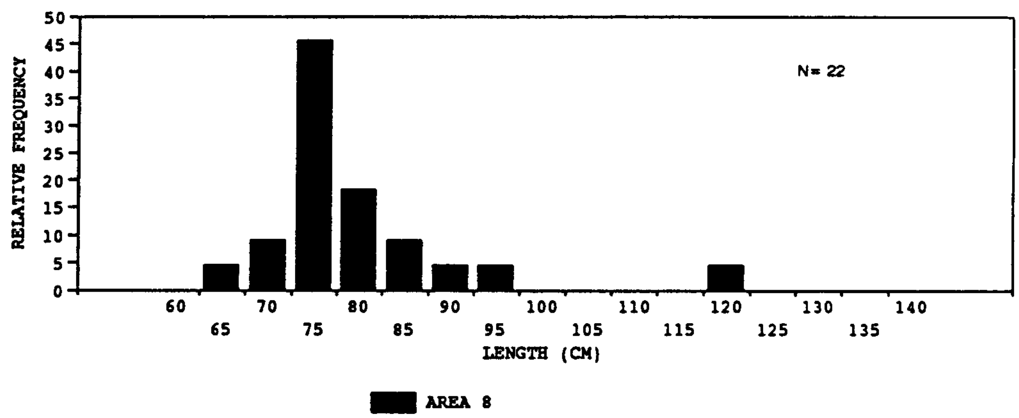


Figure 8. Length frequency distribution of speckled dace in two areas of the Little Colorado River, August 1992.

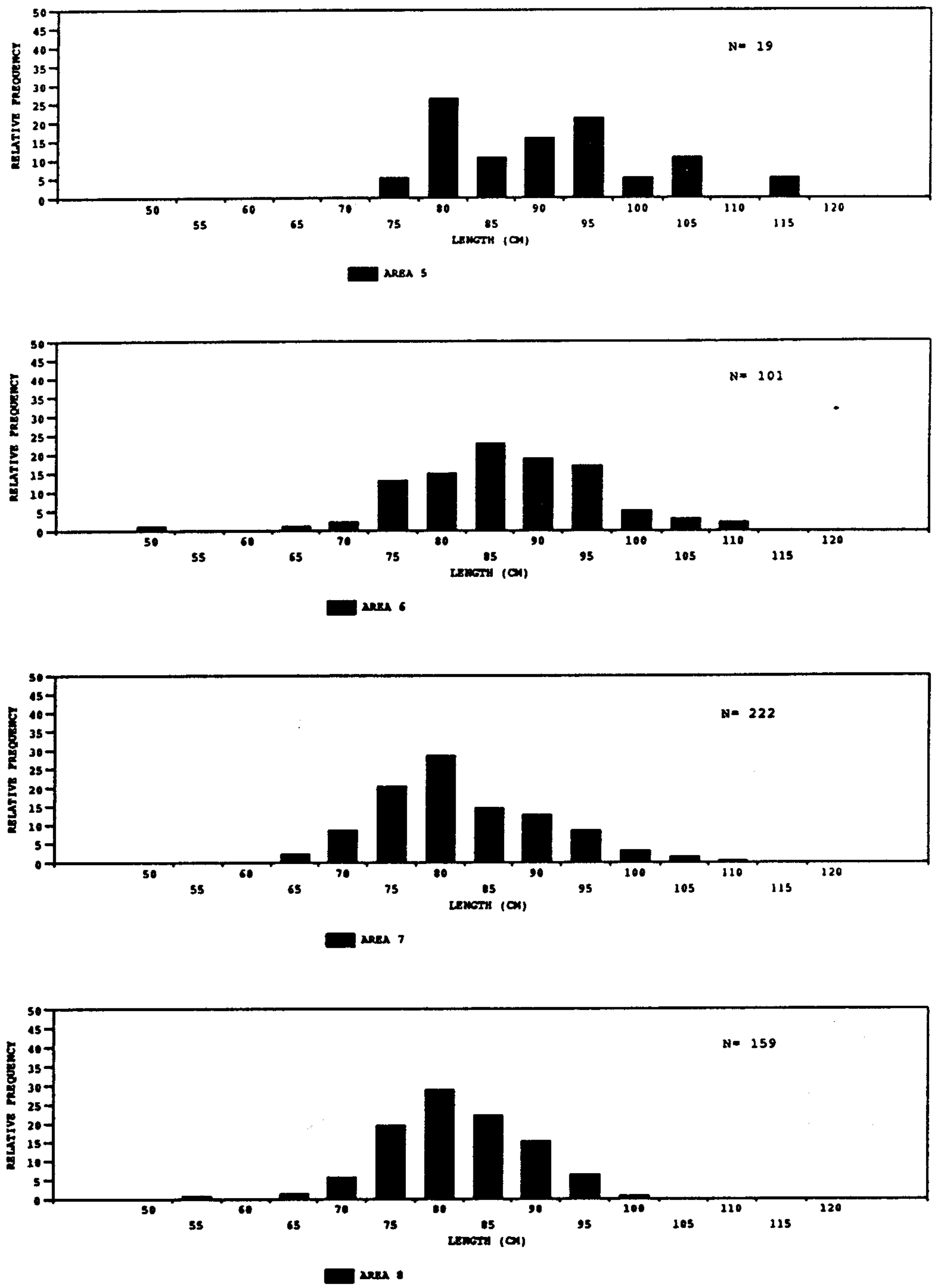


Figure 9. Length frequency distribution of speckled dace in several areas of the Little Colorado River, April 1993.

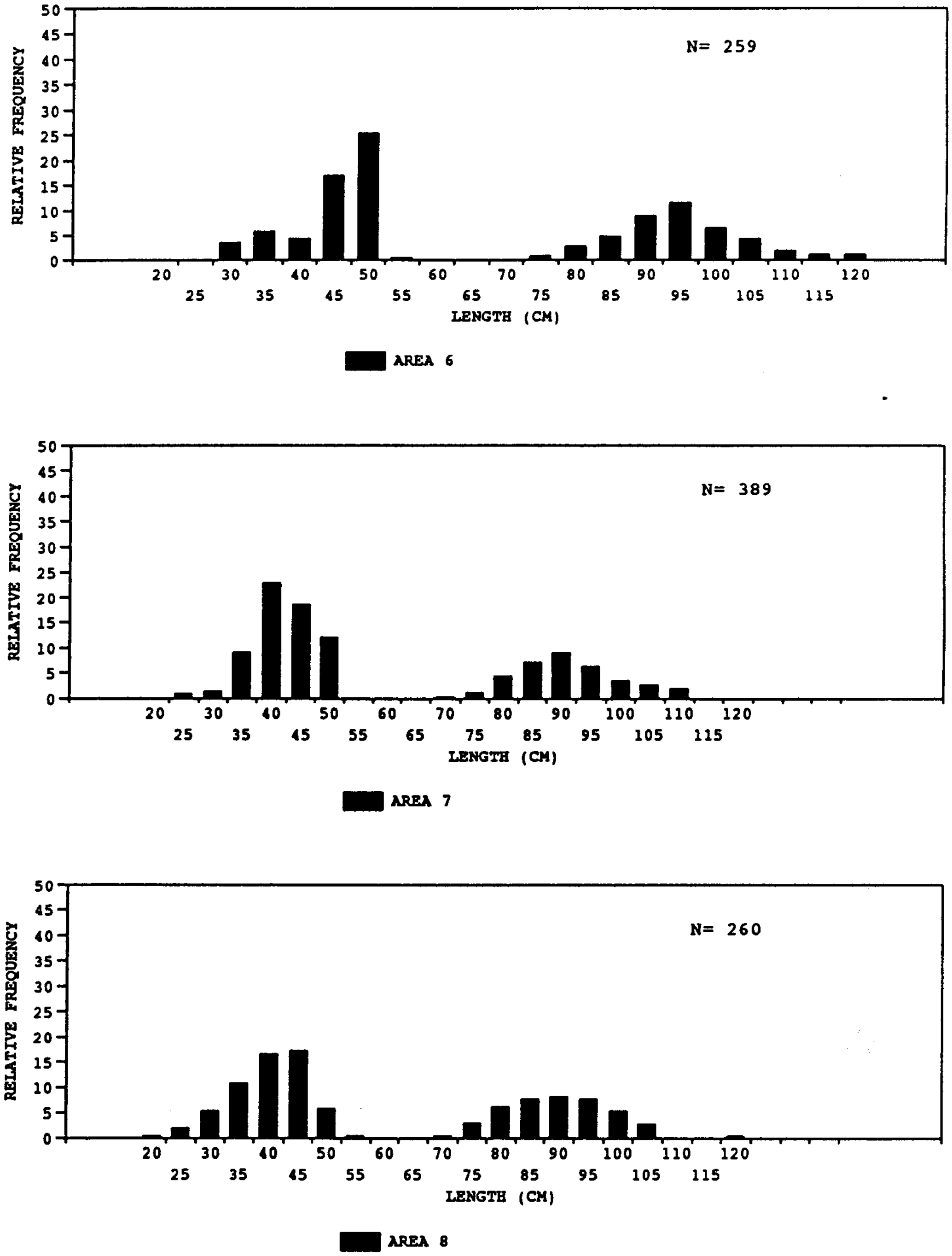


Figure 10. Length frequency distribution of speckled dace in several areas of the Little Colorado River, June 1993.

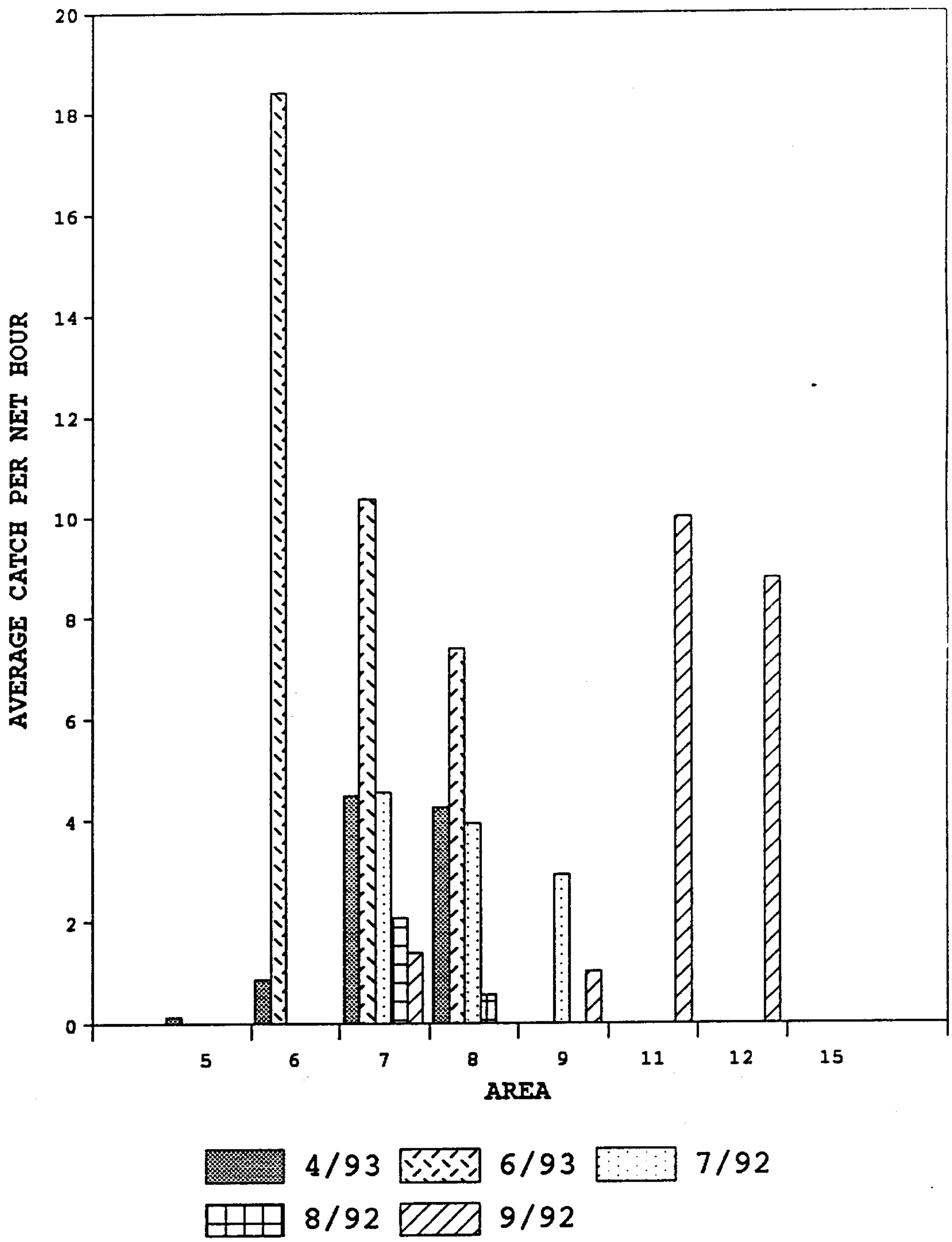


Figure 11. Average catch per net hour for speckled dace by month, from several areas of the Little Colorado River, 1992-1993.

Table 31. Number of nets fished by month for several areas on the Little Colorado River.

Month	Year	Area	Number of Nets Fished
July	1992	7	19
		8	26
		9	27
August	1992	7	61
		8	10
September	1992	7	28
		8	6
		9	24
		11	2
		12	4
		15	4
April	1993	5	15
		6	29
		7	14
		8	11
June	1993	6	10
		7	6
		8	25

69

41

APPENDIX B: SPECKLED DACE; RELATIVE FREQUENCY HISTOGRAMS OF USE TO AVAILABILITY, FOR SEVERAL AREAS ON THE LITTLE COLORADO RIVER.

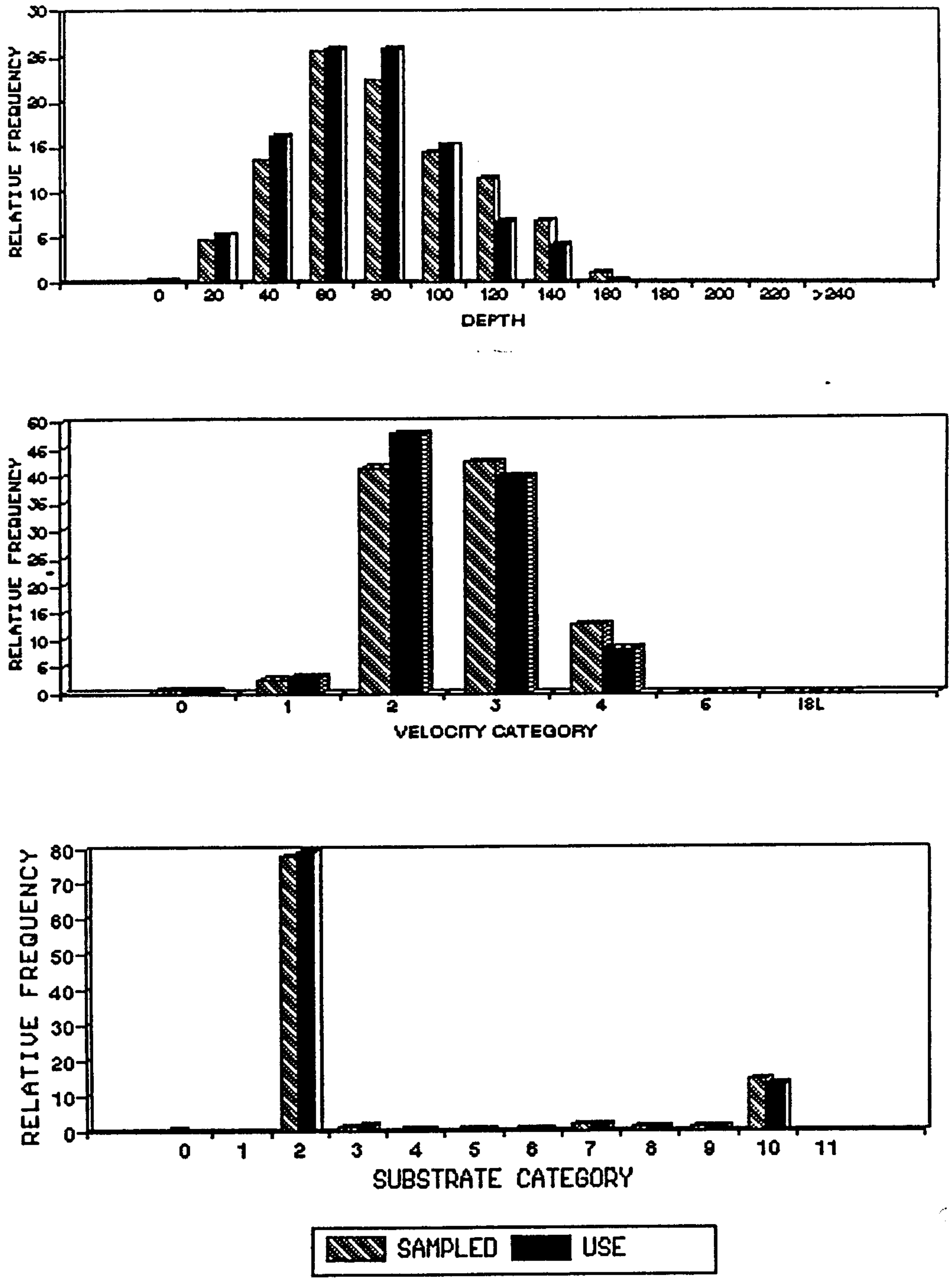


Figure 12. Relative frequency histograms of habitat that is available and used by speckled dace in area 7 of the Little Colorado River, July 1992.

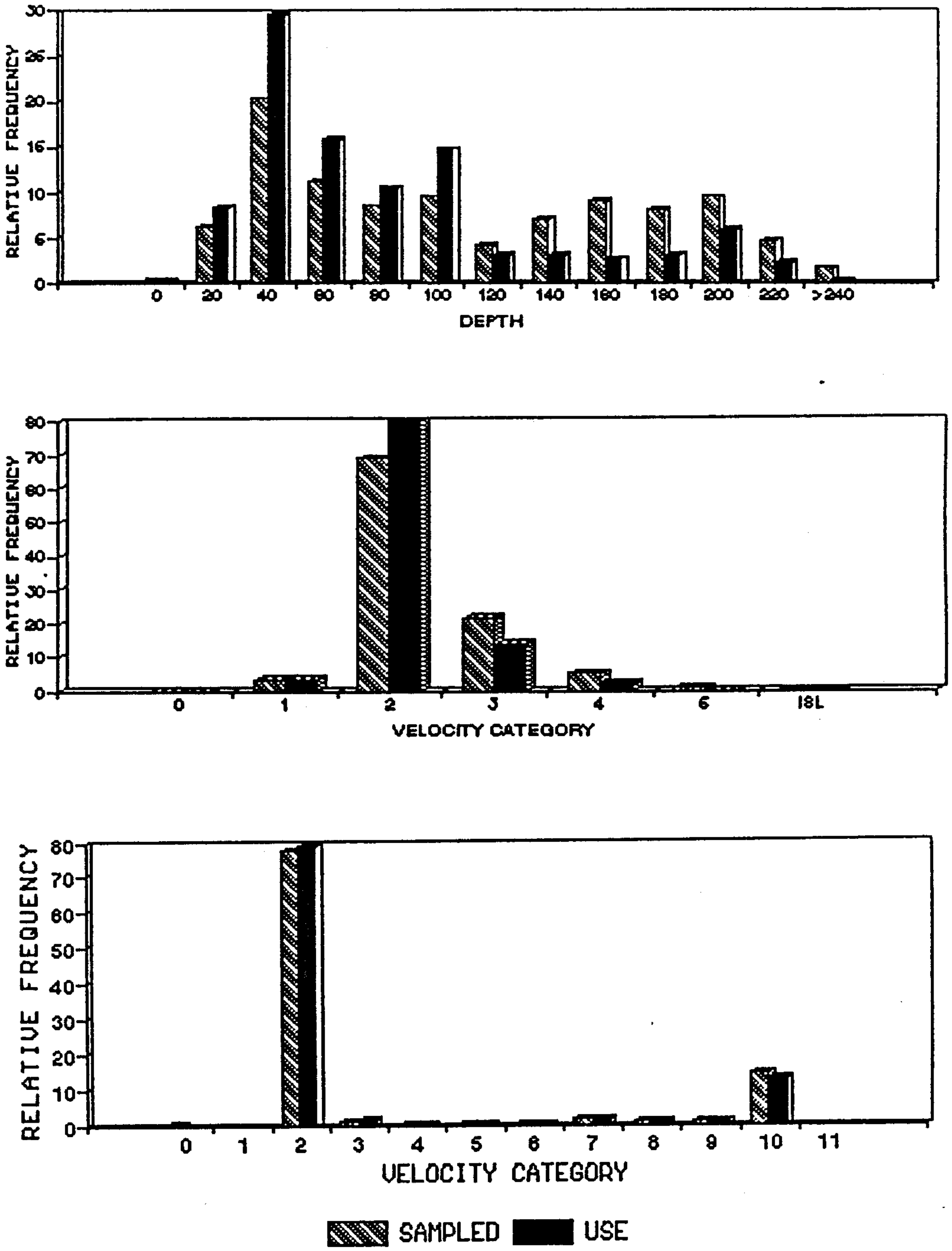


Figure 13. Relative frequency histograms of habitat that is available and used by speckled dace in area 8 of the Little Colorado River, July 1992.

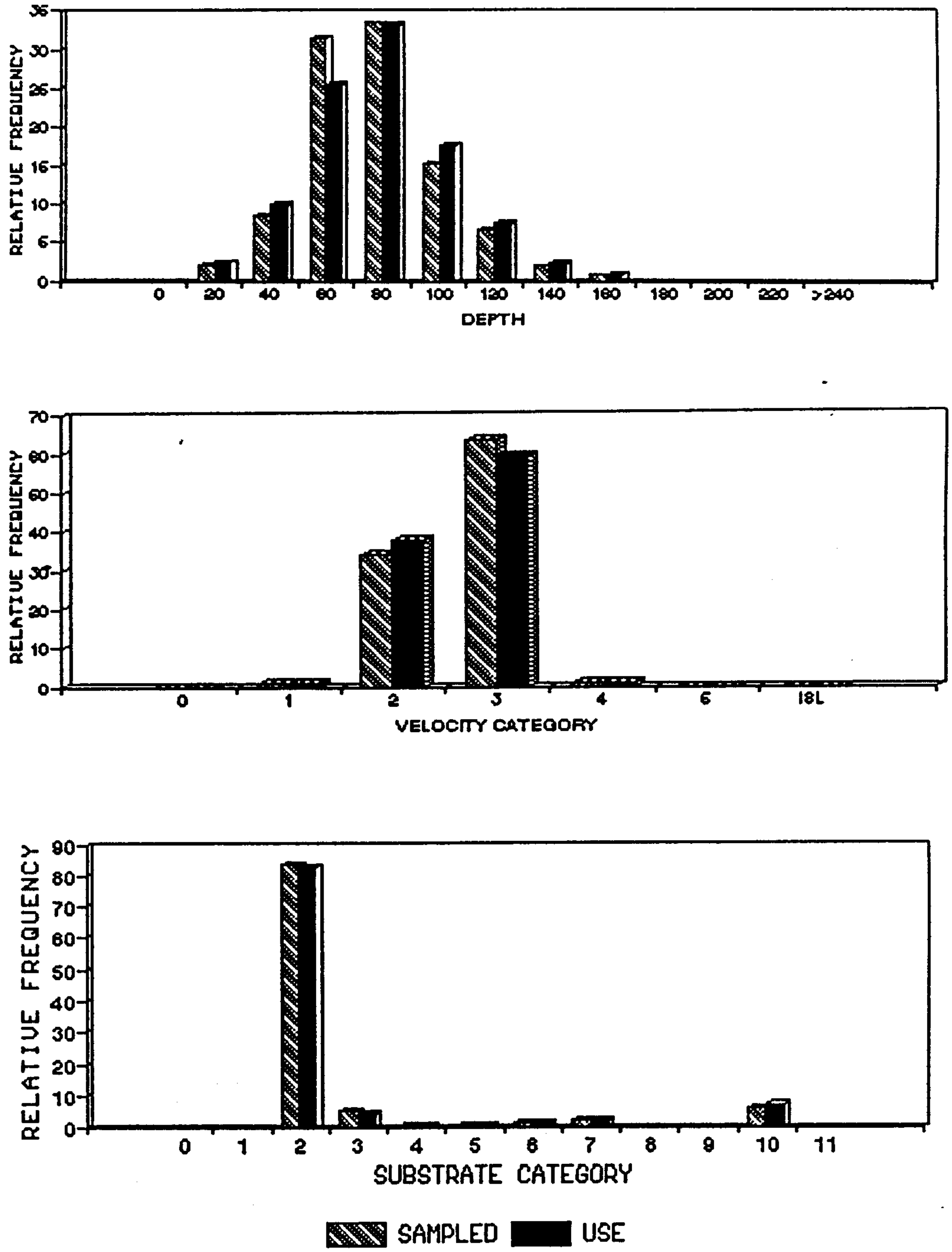


Figure 14. Relative frequency histograms of habitat that is available and used by speckled dace in area 9 of the Little Colorado River, July 1992.

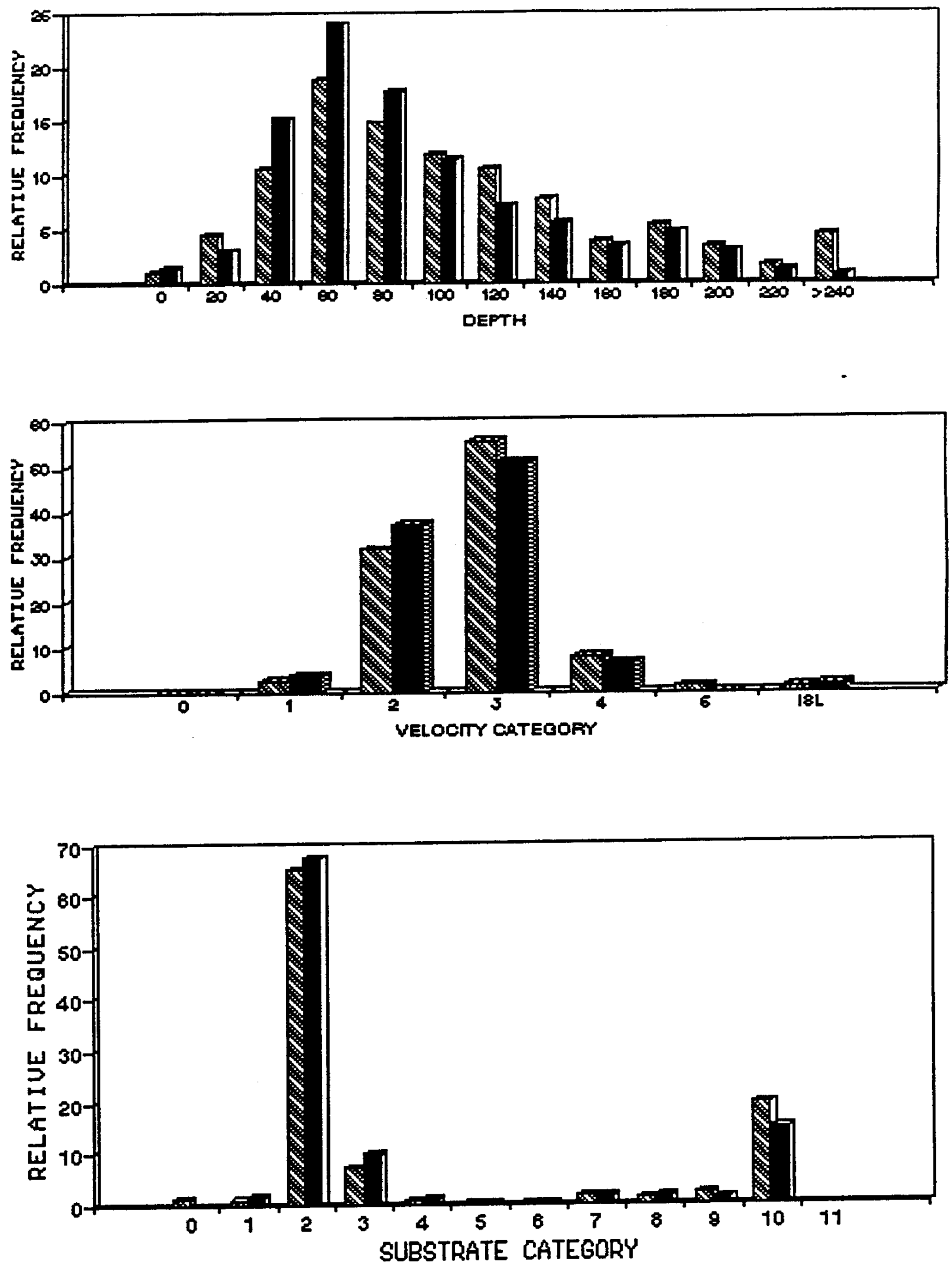


Figure 15. Relative frequency histograms of habitat that is available and used by speckled dace in area 7 of the Little Colorado River, August 1992.

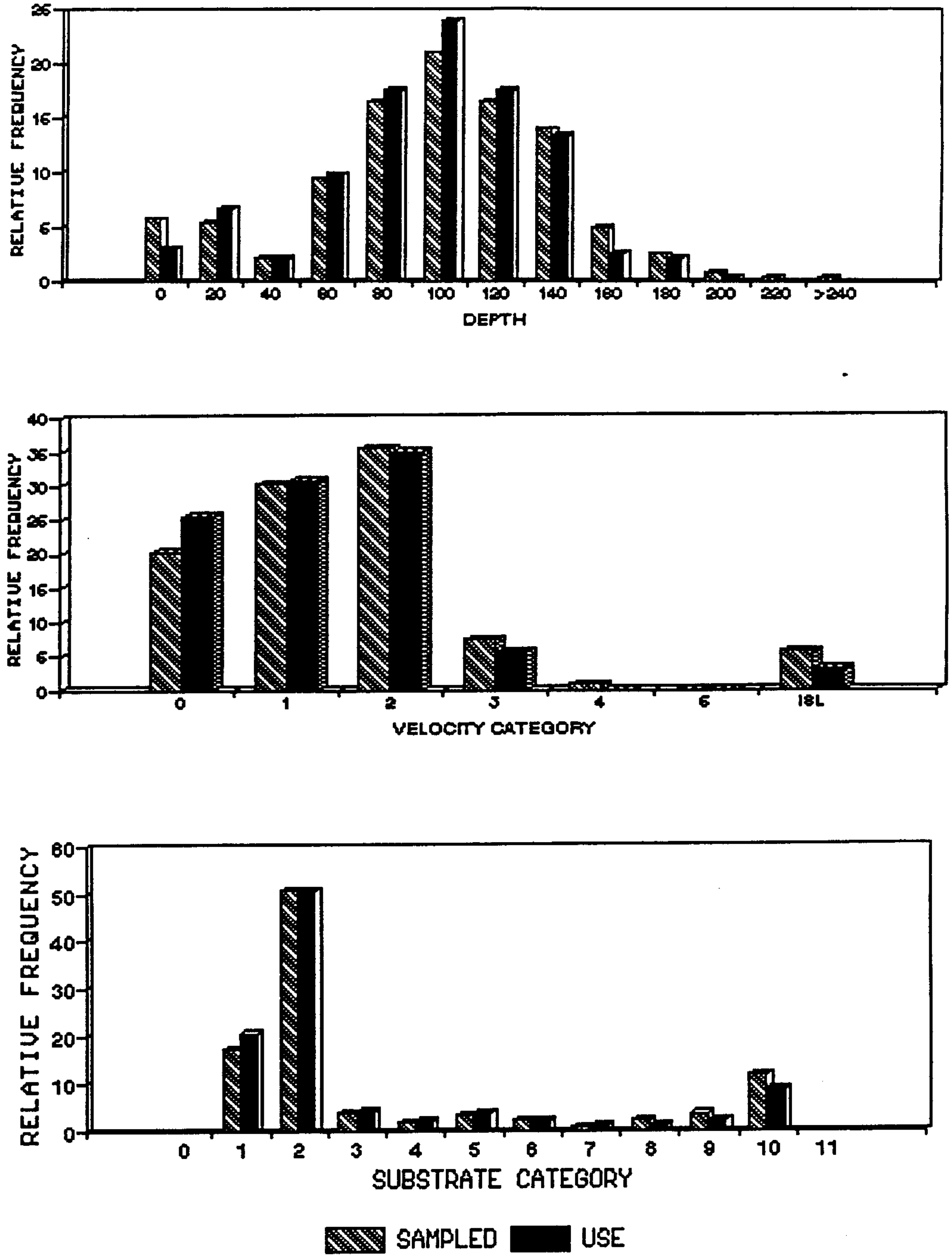


Figure 16. Relative frequency histograms of habitat that is available and used by speckled dace in area 8 of the Little Colorado River, August 1992.

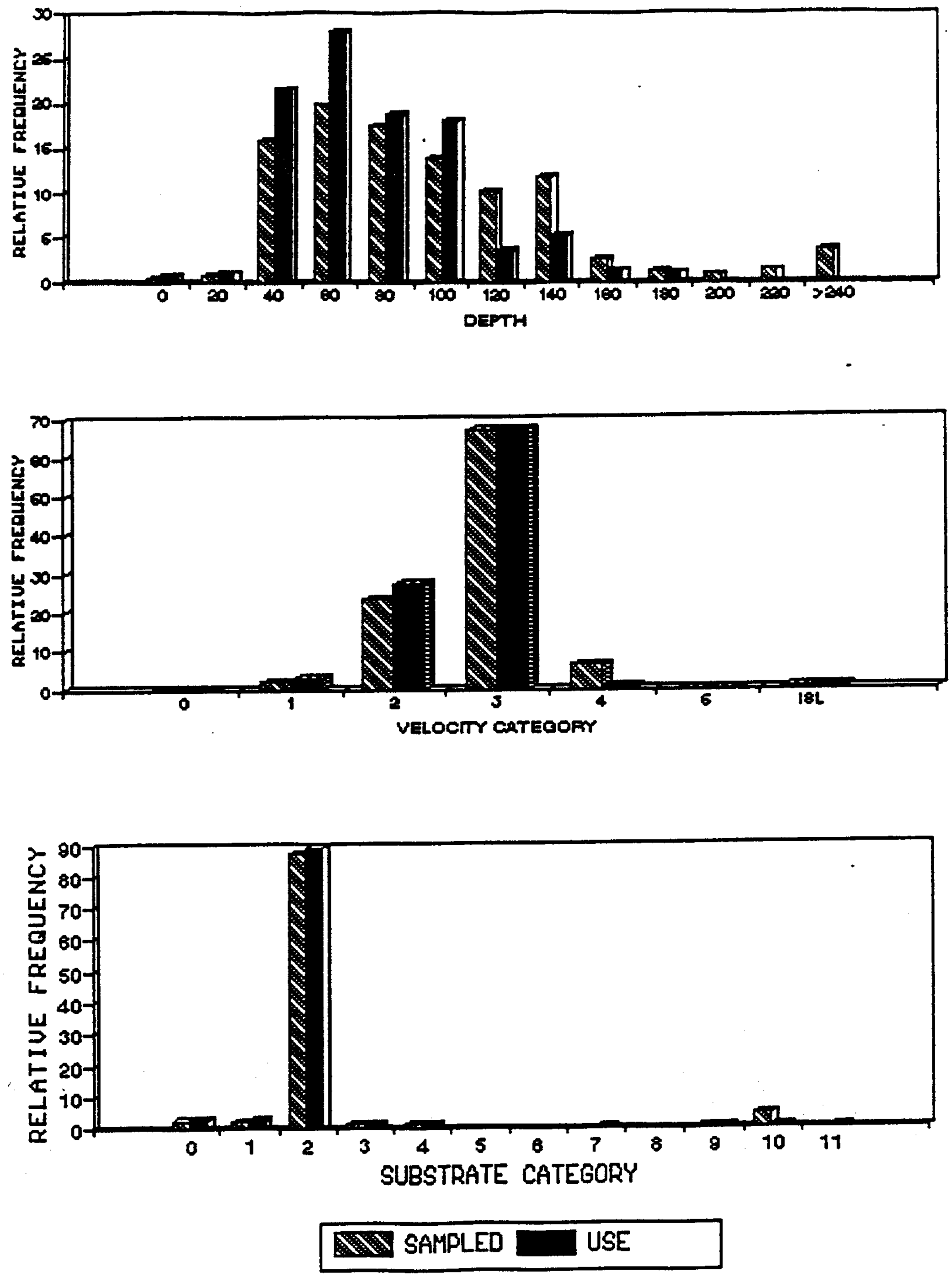


Figure 17. Relative frequency histograms of habitat that is available and used by speckled dace in area 7 of the Little Colorado River, September 1992.

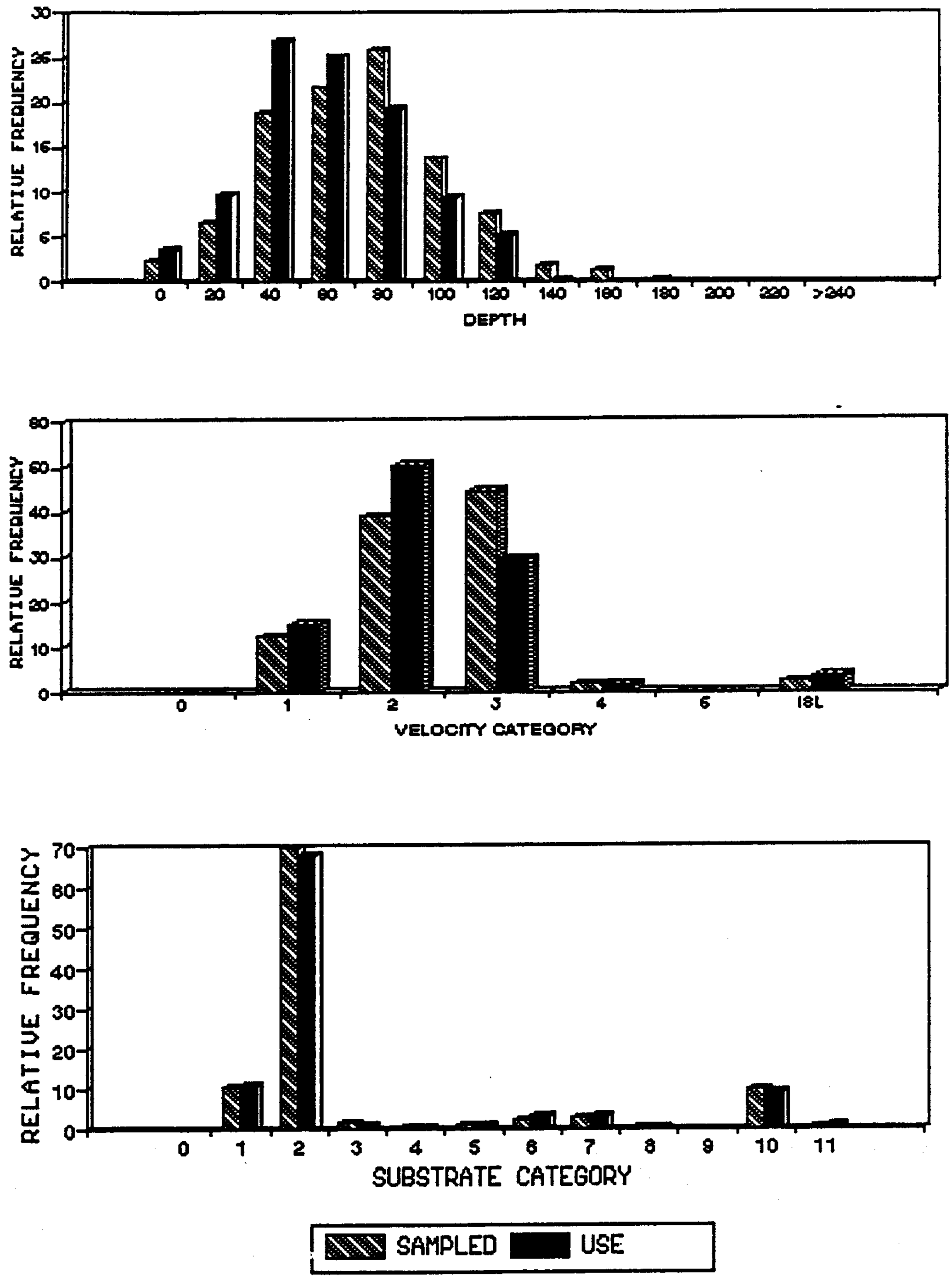


Figure 18. Relative frequency histograms of habitat that is available and used by speckled dace in area 9 of the Little Colorado River, September 1992.

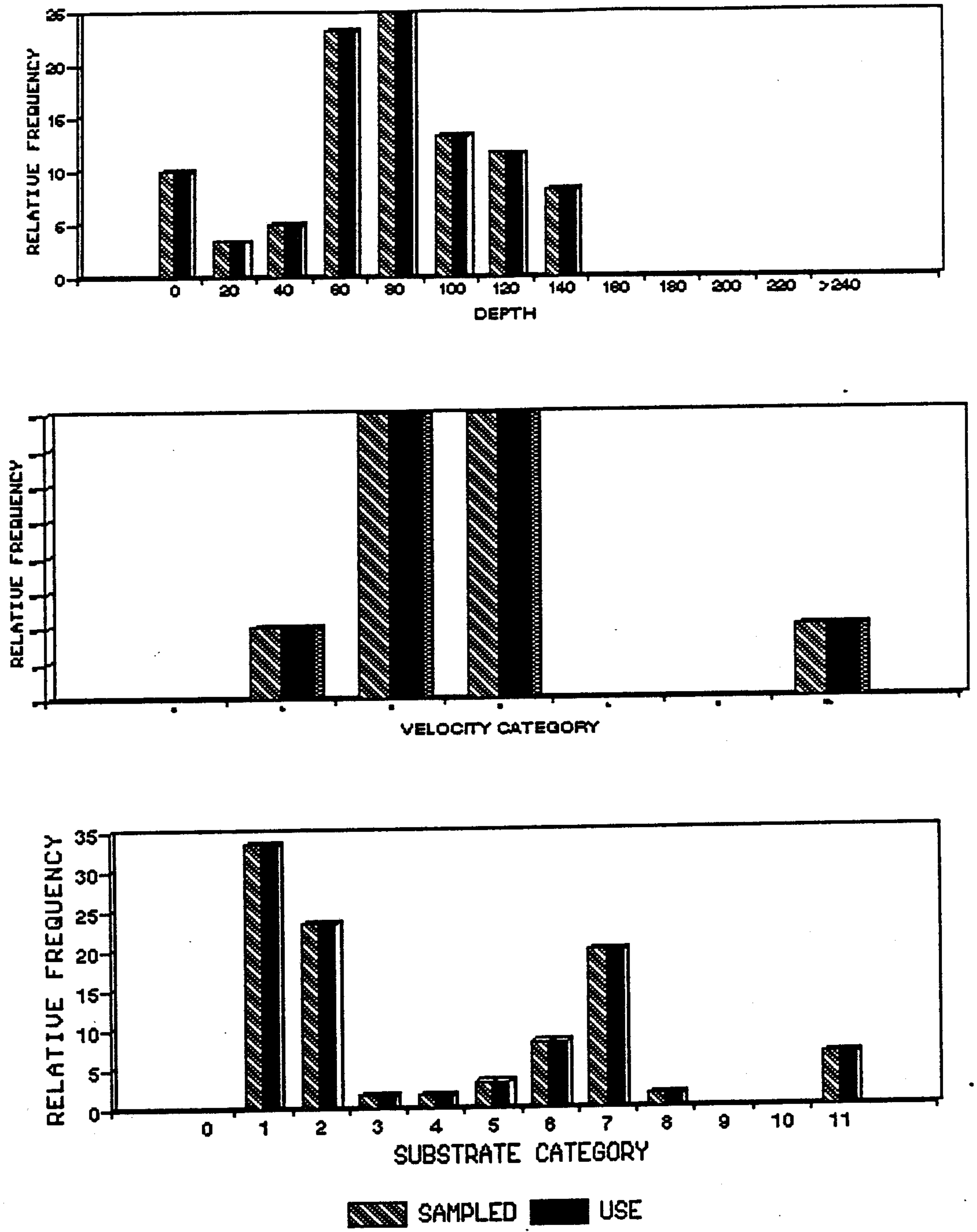


Figure 19. Relative frequency histograms of habitat that is available and used by speckled dace in area 10 of the Little Colorado River, September 1992.

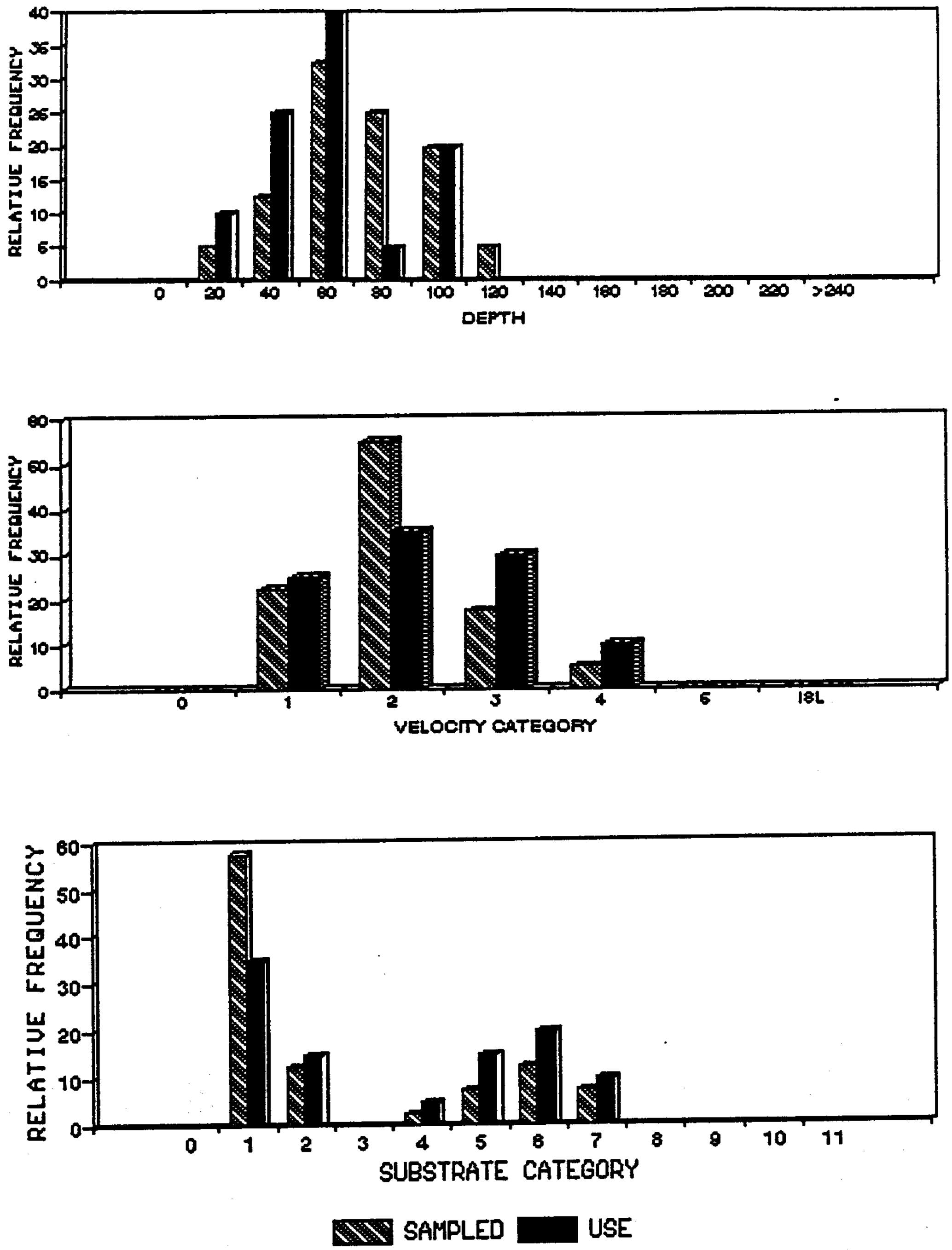


Figure 20. Relative frequency histograms of habitat that is available and used by speckled dace in area 11 of the Little Colorado River, September 1992.

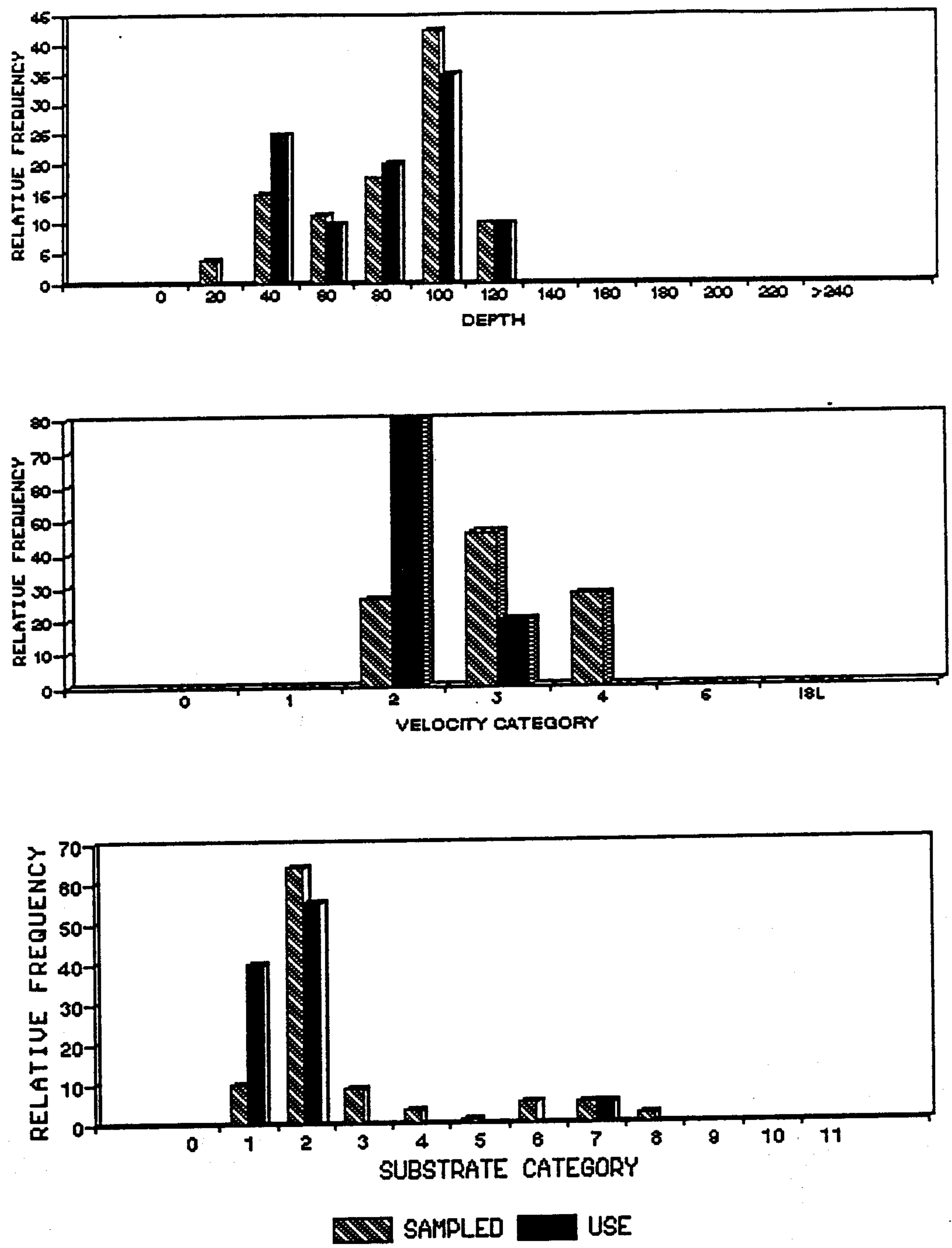


Figure 21. Relative frequency histograms of habitat that is available and used by speckled dace in area 12 of the Little Colorado River, September 1992.

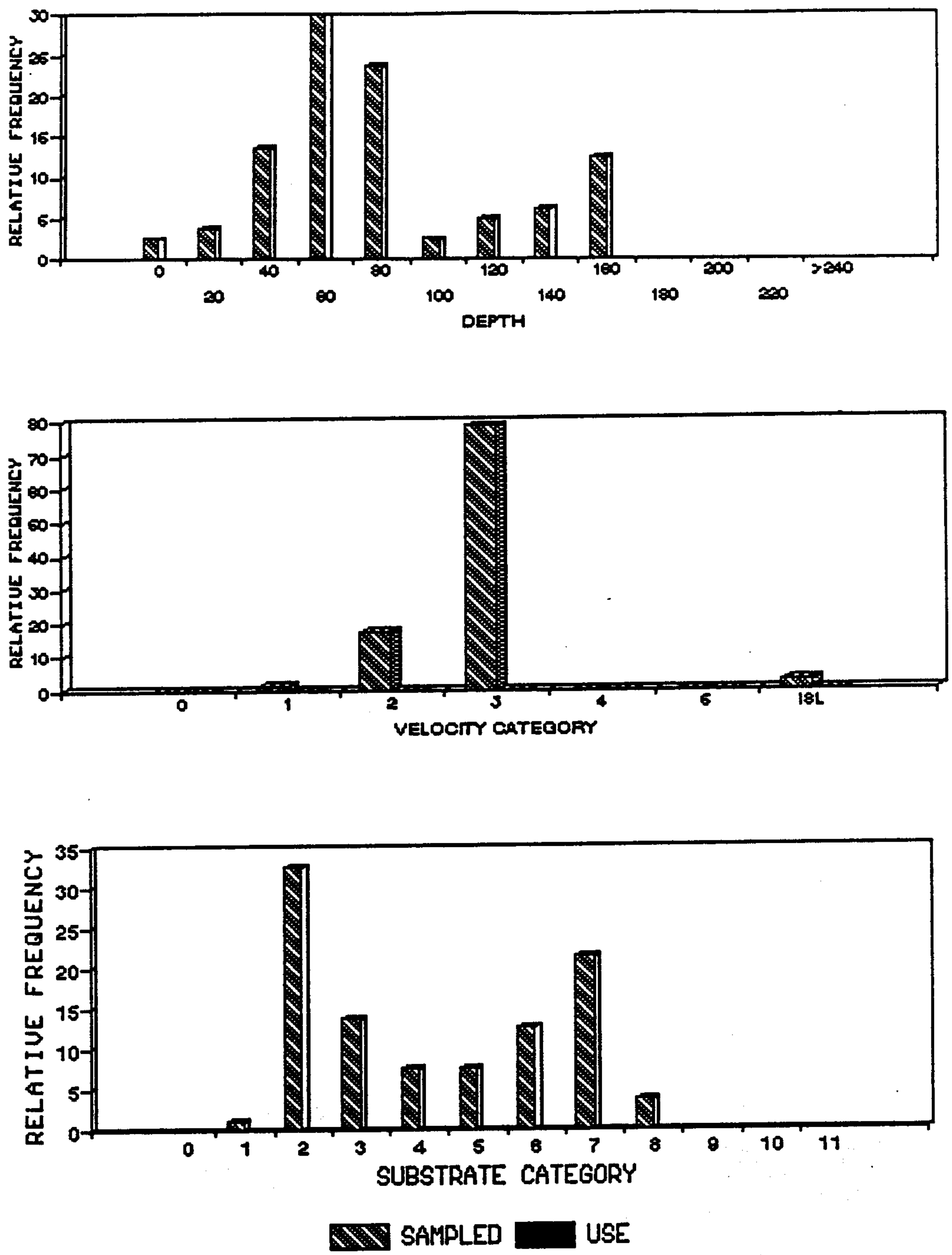


Figure 22. Relative frequency histograms of habitat that is available and used by speckled dace in area 14 of the Little Colorado River, September 1992.

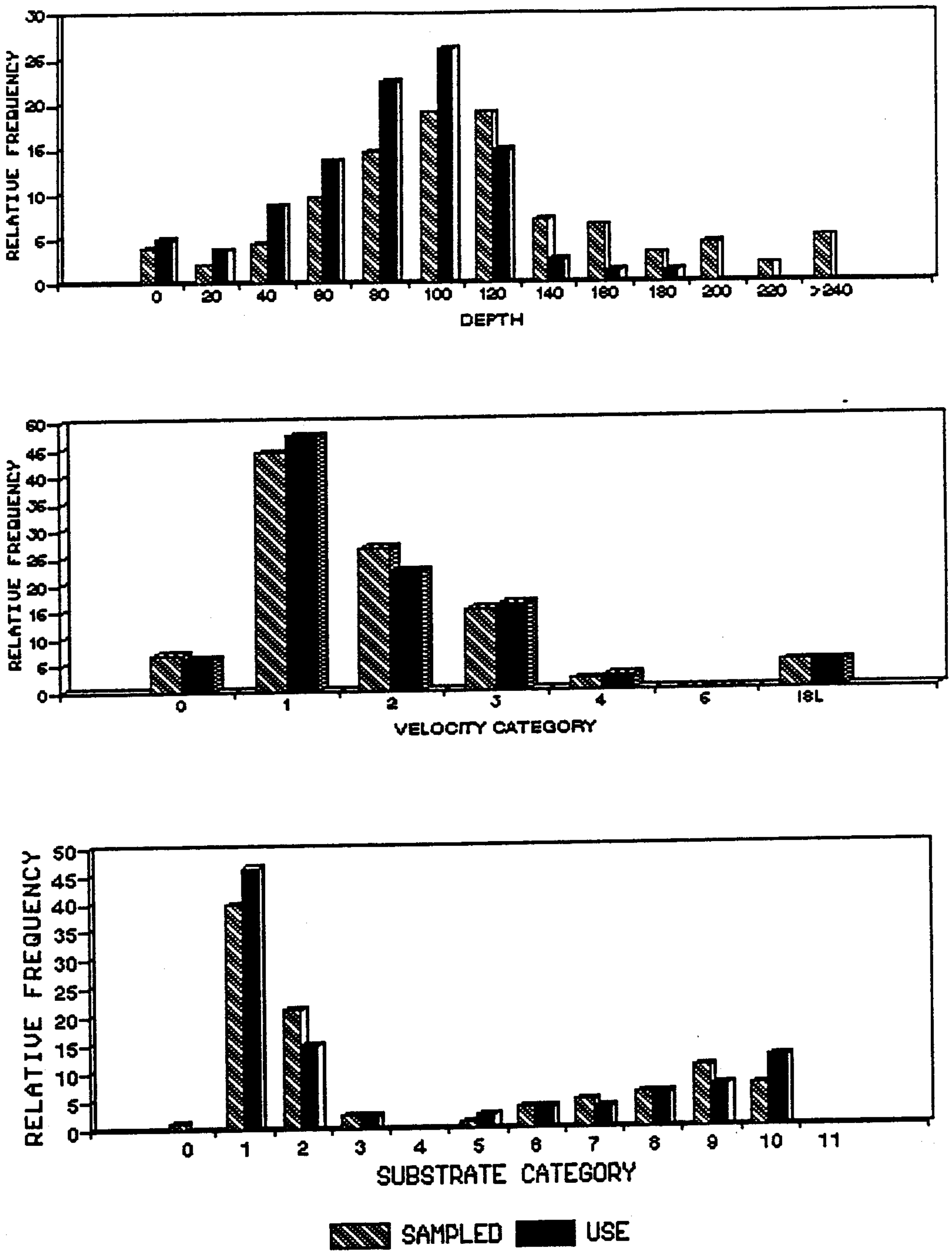


Figure 23. Relative frequency histograms of habitat that is available and used by speckled dace in area 5 of the Little Colorado River, April 1993.

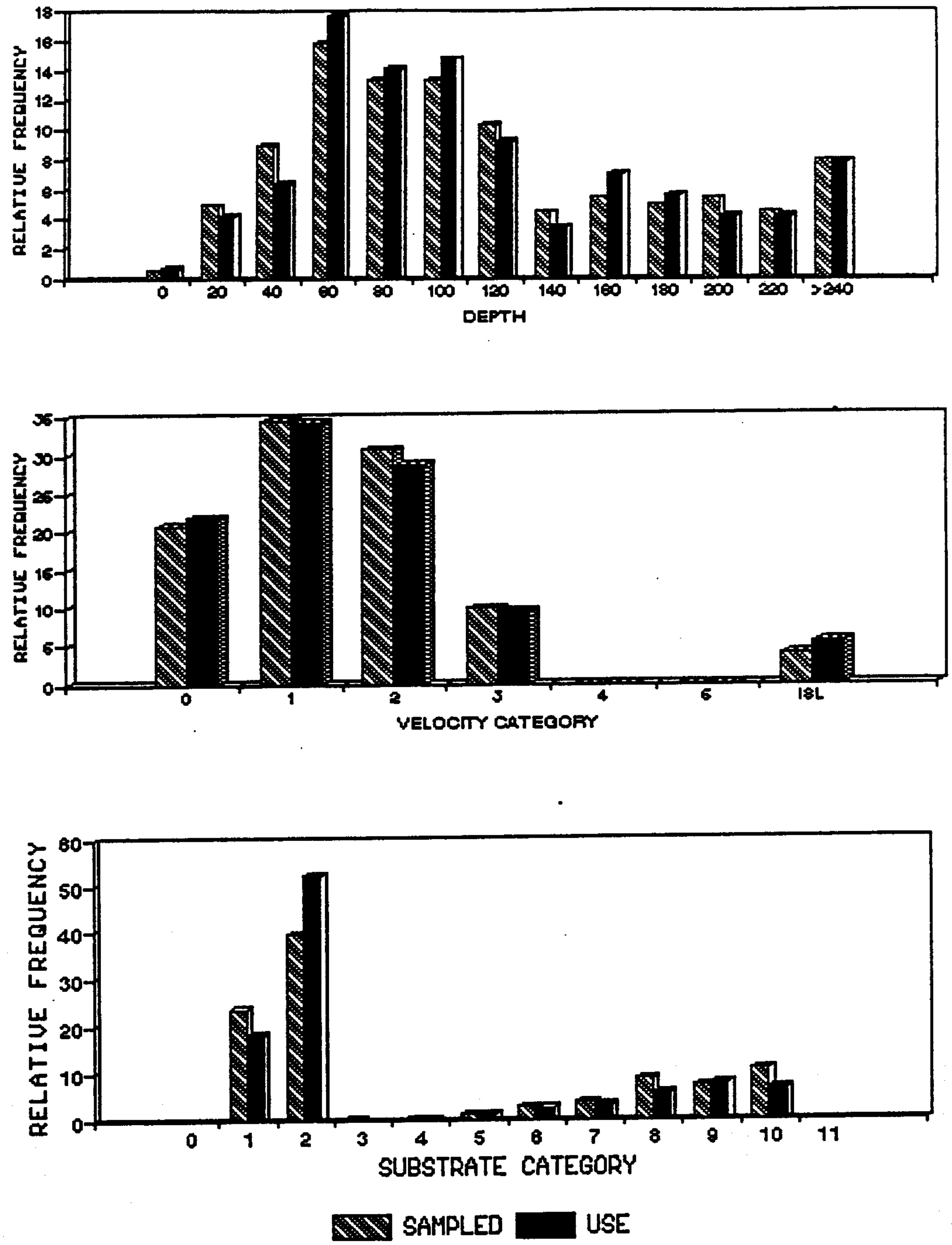


Figure 24. Relative frequency histograms of habitat that is available and used by speckled dace in area 6 of the Little Colorado River, April 1993.

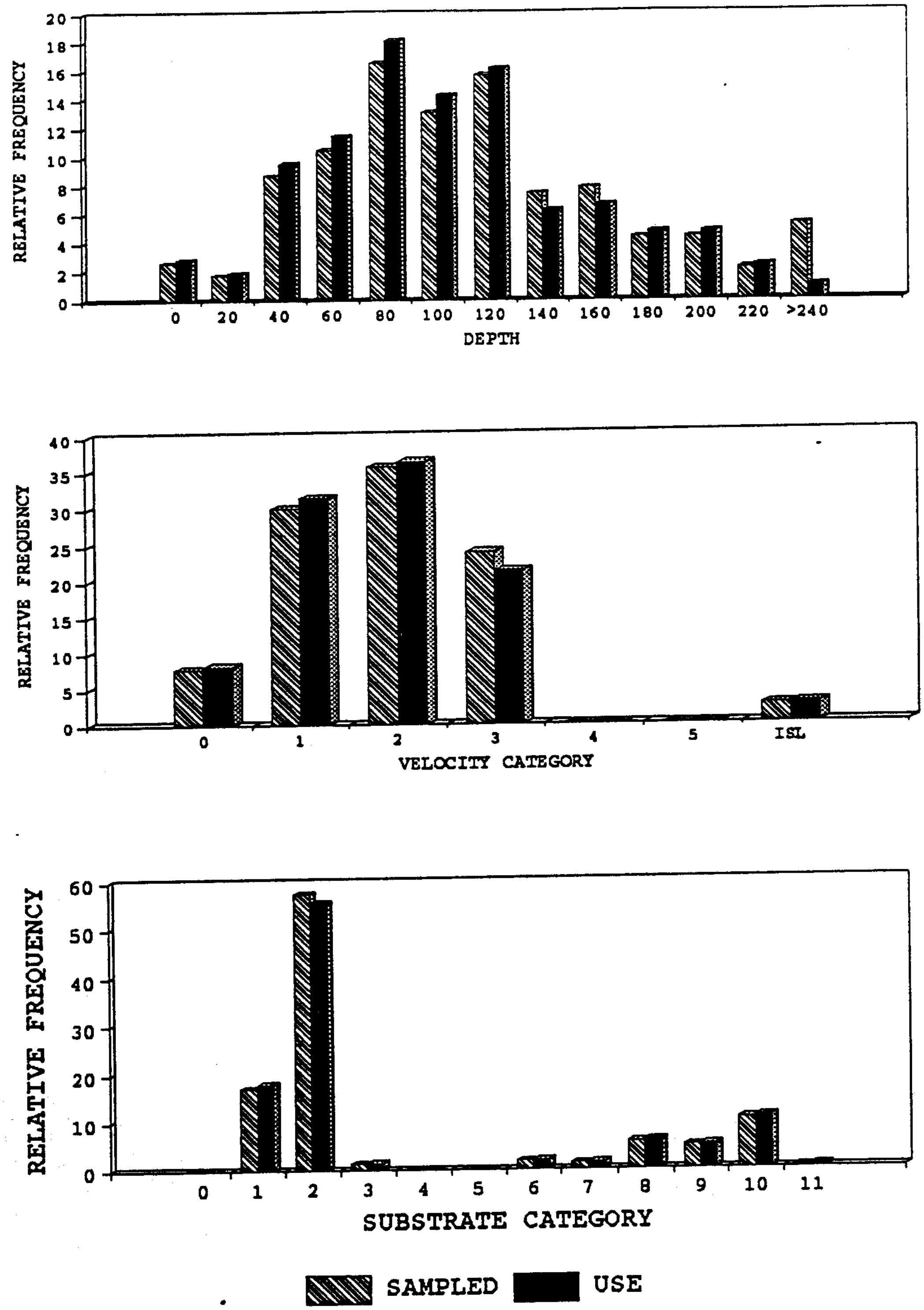


Figure 25. Relative frequency histograms of habitat that is available and used by speckled dace in area 7 of the Little Colorado River, April 1993.

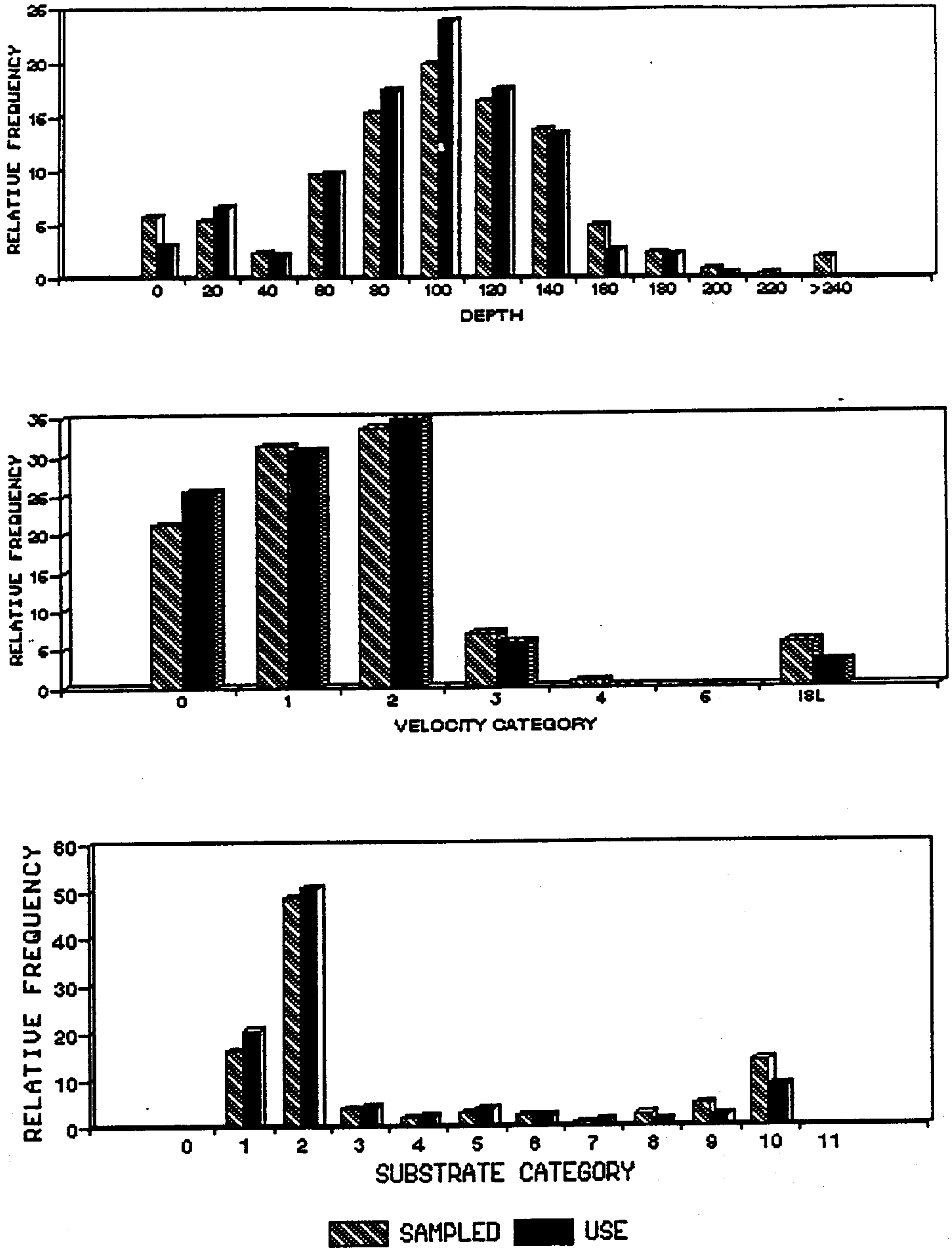


Figure 26. Relative frequency histograms of habitat that is available and used by speckled dace in area 8 of the Little Colorado River, April 1993.

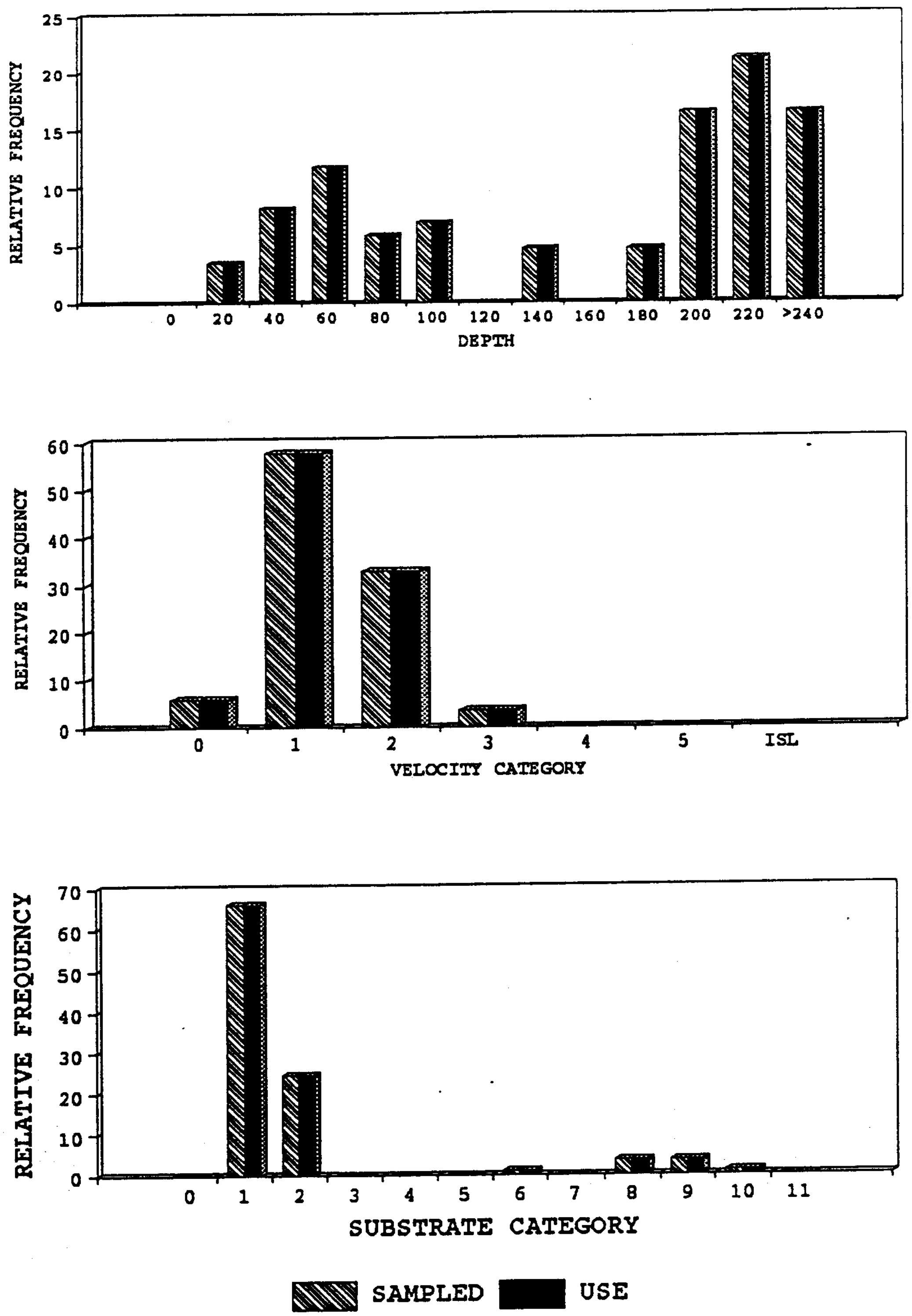


Figure 27. Relative frequency histograms of habitat that is available and used by speckled dace in area 6 of the Little Colorado River, June 1993.

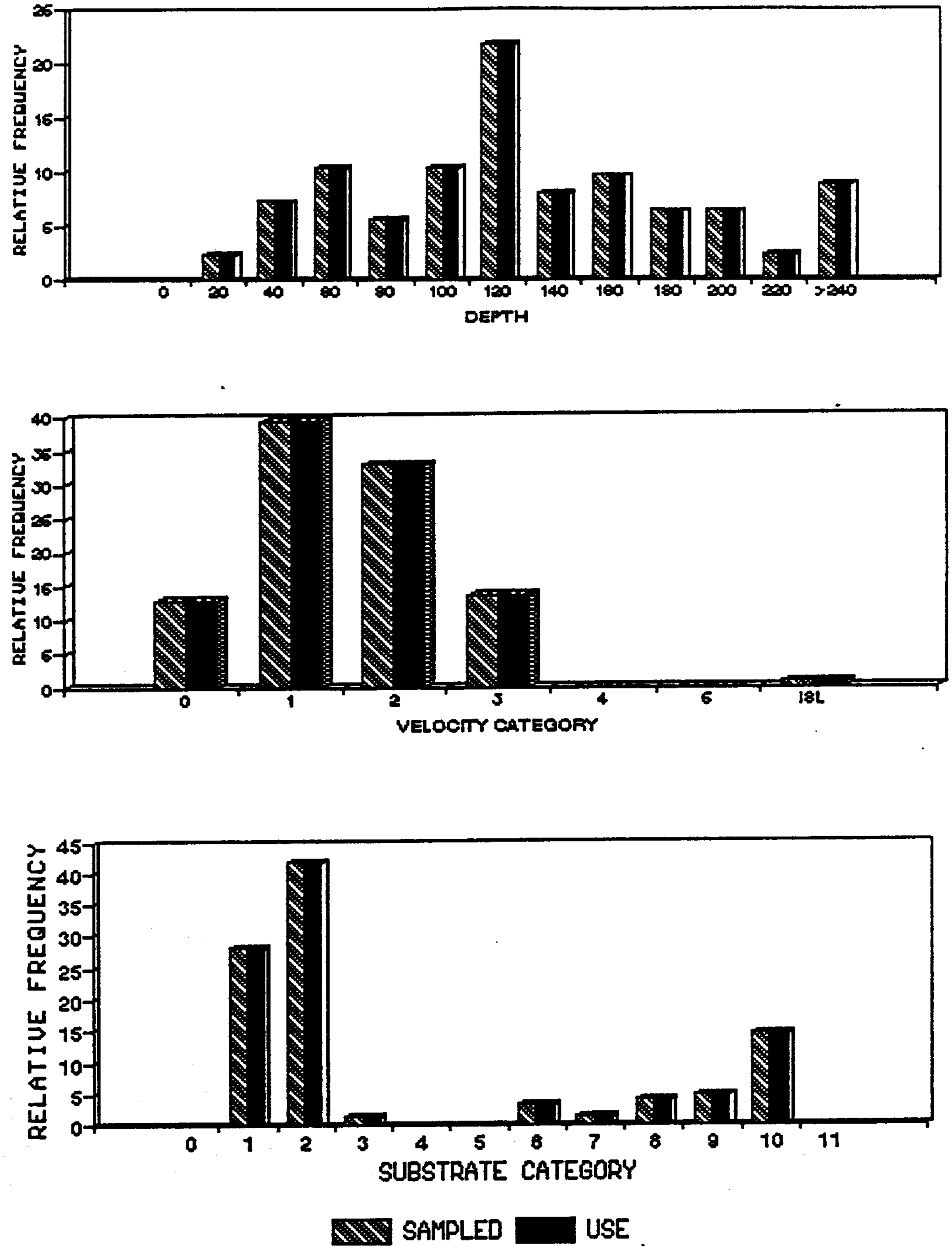


Figure 28. Relative frequency histograms of habitat that is available and used by speckled dace in area 7 of the Little Colorado River, June 1993.

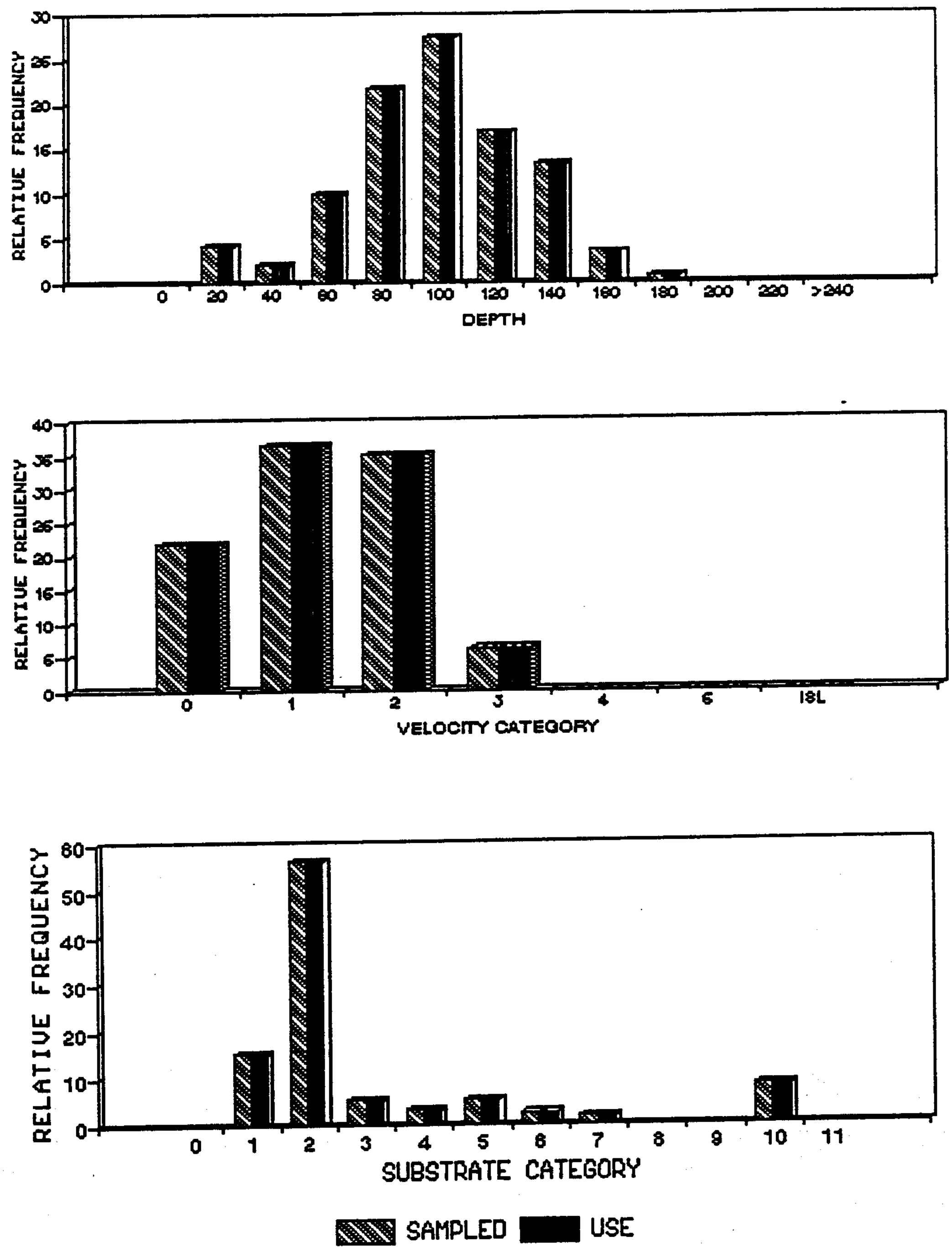


Figure 29. Relative frequency histograms of habitat that is available and used by speckled dace in area 8 of the Little Colorado River, June 1993.

Alabaster, J. S., D. W. M. Herbert, and J. Hemens. 1957. The survival of rainbow trout (*Salmo gairdnerii* Richardson) and perch (*Perca fluviatilis* L.) at various concentrations of dissolved oxygen and carbon dioxide. Annals of Applied Biology 45:177-188.

Angradi, T. R., R. W. Clarkson, D. A. Kinsolving, D. M. Kubly, and S. A. Morgensen. 1992. Glen Canyon Dam and the Colorado River: Responses of the aquatic biota to dam operations. Draft Report Prepared for the Bureau of Reclamation, Upper Colorado Region, Glen Canyon Environmental Studies, Flagstaff, AZ.

Arizona Game and Fish Department (AGF). 1993. Glen Canyon Environmental Studies Phase II 1992 Annual Report. Prepared for the Bureau of Reclamation, Upper Colorado Region, Glen Canyon Environmental Studies, Flagstaff, AZ.

Basu, S. P. 1959. Active respiration of fish in relation to ambient concentrations of oxygen and carbon dioxide. Journal of the Fisheries Research Board of Canada 16:175-212.

Behnke, R. J., and D. E. Benson. 1980. Endangered and threatened fishes of the Upper Colorado River Basin. Cooperative Extension Service, Colorado State University, Fort Collins, Colorado, USA Bulletin 503A.

Black, E. C., F. E. Fry, and V. S. Black. 1954. The influence of carbon dioxide on the utilization of oxygen by some freshwater fish. Canadian Journal of Zoology 32:408-420.

Booke H. E., B. Hollender and G. Lutterbie. 1978. Sodium bicarbonate, an inexpensive fish anesthetic for field use. Progressive Fish-Culturist 40:11-13.

Burdick, B. D., and L. R. Kaeding. 1985. Reproductive ecology of the humpback chub and the roundtail chub in the Upper Colorado River. Proceedings of the Western Association of Fish and Wildl. Agencies and the Western Division of the American Fisheries Society 1985:163.

Carothers, S. W., and S. W. Aitchison. 1972 . Blue Springs (mi. 13, Little Colorado River) as a barrier to distribution of speckled dace (*Rhinichthys osculus* Girard), (Cyprinidae). Preliminary report (1971) and request for additional support (1972). Grand Canyon Natural History Association. Grand Canyon Reference Library, 597.09. 9 pp.

Carothers, S. W., and B. T. Brown. 1991. The Colorado River through Grand Canyon. University of Arizona Press, Tucson, Arizona, USA.

Claiborne J. B., and N. Heisler. 1984. Acid-base regulation and ion transfers in the carp (Cyprinus carpio) during and after exposure to environmental hypercapnia. Journal of Experimental Biology 108:25-43.

Cole, G. A. 1975. Calcite saturation in Arizona waters. International Association of Theoretical and Applied Limnology. (Verh. Internat. Verein. Limnol.) 19:1675-1685.

Cole, G. A. 1983. Textbook of limnology, 3rd edition. Waveland Press, Inc. Prospect Heights, Ilinois, USA.

Cole G. A., and D. M. Kubly. 1976. Limnological studies on the Colorado River from Lees Ferry to Diamond Creek. Colorado River Research Program, Grand Canyon National Park, Technical Report 8, Grand Canyon, Arizona, USA.

Dahlberg, M. L., D. L. Shumway, and P. Doudoroff. 1968. Influence of dissolved oxygen and carbon dioxide on swimming performance of largemouth bass and coho salmon. Journal of the Fisheries Research Board of Canada 25:49-70.

Eaton, D. M. 1993. Ecology of arctic grayling in Becharof Lake tributaries. Master Thesis, University of Arizona. Tucson, Arizona, USA.

Eddy F. B., J. P. Lomholt, R. E. Weber, and K. Johansen. 1977. Blood respiratory properties of rainbow trout (*Salmo gairdneri*) kept in water of high CO_2 tension. Journal of Experimental Biology 67:37-47.

Fish, F. F. 1943. The anaesthesia of fish by high carbon dioxide concentrations. Transactions of the American Fisheries Society 72:25-29.

Fry, F. E. J., V. S. Black, and E. C. Black. 1947. Influence of temperature on the asphyxiation of young goldfish (*Carassius auratus*) under various tensions of oxygen and carbon dioxide. Biological Bulletin 92:217-224.

Gorman, O. T., and J. R. Karr. 1978. Habitat structure and stream fish communities. Ecology 59:507-515.

Gorman, O. T., S. C. Leon, and O. E. Maughan. 1992. Habitat use by humpback chub, Gila cypha, in the Little Colorado River and other tributaries of the Colorado River. Draft EIS Technical Report, December 1991. Pinetop, FAO. 18pp.

Hach Company. 1989. Water analysis handbook. Hach Company, Loveland, Colorado.

Hamman, R. L. 1982. Spawning and culture of humpback chub. Progressive Fish-Culturist 44:213-216.

Hem, J. D. Study and interpretation of the chemical characteristics of natural water, Second edition. Geological Survey Water-Supply Paper 1473. 363 pp.

Hereford, R. 1984. Climate and ephemeral-stream processes: Twentieth-century geomorphology and alluvial stratigraphy of the Little Colorado River, Arizona. Geological Society of America Bulletin 65:654-668.

Holden, P.B. 1978. A study of the habitat use and movement of the rare fishes in the Green River, Utah. The American Fisheries Society Bonneville Chapter Proceedings 107:64-89.

Holden, P. B., and C. B. Stalnaker. 1975. Distribution and abundance of mainstream fishes of the middle and upper Colorado River basins, 1967-1973. Transactions of the American Fisheries Society 104:217-231.

Ito, P. K. 1980. Robustness of ANOVA and MANOVA test procedures. Pages 199-236 *in* P. R. Krishnaiah, editor. Handbook of statistics, volume 1. Amsterdam, North-Holland.

Janssen, R. G., and D. J. Randall. 1975. The effects of changes in pH and in PCO_2 in blood and water on breathing in rainbow trout, *Salmo gairdneri*. Respiratory Physiolology 25:235-245.

Johnson, P. W., and R. B. Sanderson. 1968. Spring flow into the Colorado River- Lees Ferry to Lake Mead, Arizona. Water-Resource Report No. 34. Arizona State Land Department.

Kaeding, L. R., and M. A. Zimmerman. 1983. Life history and ecology of the humpback chub in the Little Colorado and Colorado rivers of the Grand Canyon. Transactions of the American Fisheries Society 112:557-594.

Kaeding, L. R., B. D. Burdick, P. A. Schrader, and C. W. McAda. 1990. Temporal and spatial relations between the spawning of humpback chub and roundtail chub in the Upper Colorado River. Transactions of the American Fisheries Society 119:135-144.

Kubly, D. M. 1990. The endangered humpback chub (*Gila cypha*) in Arizona a review of past studies and suggestions for future research (Draft). Report to the U.S. Bureau of Reclamation, Salt Lake City.

Maddux, H. R., D. M. Kubly, J. C. deVoss, W. R. Persons, R. Staedicke, R. L. Wright. 1987. Effects of varied flow regimes on aquatic resources of Glen and Grand Canyons. Arizona Game and Fish Dept. Final Rep. to U.S. Bureau of Reclamation.

Miller, R. R. 1946. Gila cypha, a remarkable new species of cyprinid fish from the Colorado River in Grand Canyon, Arizona. Journal of the Washington Academy of Sciences 36:409-415.

Miller, R. R. 1963. Distribution, variation, and ecology of *Lepidomeda vittata*, a rare cyprinid fish endemic to eastern Arizona. Copeia 1963:1-5.

Minckley, C. O., S. W. Carothers, J. W. Jordan, and H. D. Usher. 1980. Observations on the humpback chub, *Gila cypha*, within the Colorado and Little Colorado rivers, Grand Canyon National Park, Arizona. United States National Park Service Transactions and Proceedings Series 8:176-183.

Minckley, C. O. 1977. A preliminary survey of the fish of the Little Colorado River from Blue Spring to the vicinity of Big Canyon, Coconino County, Arizona. Report to the Office of Endangered Species, Region II, U.S. Fish and wildlife Service. Albuquerue, New Mexico.

Minckley, W. L. 1973. Fishes of Arizona. Sims Printing Co., Inc. Phoenix, Arzona, USA.

Mishra B. K., D. Kumar, and R. Mishra. 1983. Observations on the use of carbonic acid anaesthesia in fish fry transport. Aquaculture 32:405-408.

Moyle P. B., and J. J. Cech, Jr. 1988. Fishes; an introduction to ichthyology, 2nd edition. Prentice Hall, Englewood Cliffs, New Jersey, USA.

Norusis, M. J. 1990. SPSS base system user's guide. SPSS Inc. Chicago, Ilinois, USA.

Ott L. 1988. An introduction to statistical methods and data analysis, 3rk edition. PWS-Kent Publishing Co., Boston, Massachusetts, USA.

Pankow J. F. 1991. Aquatic chemistry concepts. Lewis Publishers, Chelsea, Michigan, USA.

Post G. 1979. Carbonic acid anesthesia for aquatic organsms. Progressive Fish-Culturist 41:142-144.

Powers, E. B. 1937. Factors involved in the sudden mortality of fishes. Transactions of the American Fisheries Society 67:271-281.

Rinne, J. N., and W. L. Minckley. 1991. Native fishes of arid lands: a dwindling resource of the desert Southwest. Gen. Tech. Rep. RM-206. Ft. Collins, CO: U.S. Deptartment of Agriculture, Forest Service, Rocky Mountain For. and Range Experiment Station. 45pp.

Shelford, V. E. and W. C. Allee. 1912. An index of fish environments. Science 36:76-77.

Slauson, W.L. 1988. Graphical and statistical procedures for comparing habitat suitability data. U.S. Fish Wildl. Service Biological Report 89(6). 58 pp.

American Public Health Association, Inc. (APHA). 1965. Standard methods for the examination of water and wastewater, 12th edition. Boyd Printing Co., Inc., Albany, New York, USA.

Stumm, W., and J. J. Morgan. 1970. Aquatic chemistry an introduction emphasizing chemical equilibria in natural waters. Wiley-Interscience, New York, New York, USA.

Suttkus, R. D., and G. H. Clemmer. 1979. Fishes of the Colorado River in Grand Canyon National Park. United States National Park Service Transactions and Proceedings Series 5:599-604.

Takeda T. and Y. Itazawa. 1983. Possibility of applying anesthesia by carbon dioxide in the transportation of live fish. Bulletin Japanese Society of Science and Fisheries 49:725-731.

U. S. Department of the Interior (USDOI). 1988. Glen Canyon Environmental Studies Final Report. January 1980. 86pp.

United States Department of Agriculture (USDA). 1981a. Little Colorado River Basin Cooperative Study; Arizona-New Mexico Summary Report. U.S. Soil Conservation Service, USDA Economic Research Service, U.S. Forest Service, Arizona Department of Water Resources New Mexico State Engineer Office. 72/2/Summary.

United States Department of Agriculture (USDA). 1981b. Little Colorado River Basin Cooperative Study; Arizona-New Mexico Appendix I, Description of Basin. U.S. Soil Conservation Service, USDA Economic Research Service, U.S. Forest Service, Arizona Department of Water Resources New Mexico State Engineer Office. 72/2/APP.1.

United States Department of Agriculture (USDA). 1981b. Little Colorado River Basin Cooperative Study; Arizona-New Mexico Appendix IV, Recreation, Fish and Wildlife, and Timber. U.S. Soil Conservation Service, USDA Economic Research Service, U.S. Forest Service, Arizona Department of Water Resources New Mexico State Engineer Office. 72/2/APP.4.

U.S. Fish and Wildlife Service (USFWS). 1990. Humpback chub recovery plan. USFWS Denver, Colorado, USA. 43pp.

U. S. Geological Survey (USGS). 1988a. Salt Trail Canyon Arizona-Coconino 7.5 minute quadrangle. U.S. Department of the Interior Geological Survey, Denver, Colorado, USA.

U. S. Geological Survey (USGS). 1988b. Blue Springs Arizona-Coconino 7.5 minute quadrangle. U.S. Department of the Interior Geological Survey, Denver, Colorado, USA.

Valdez, R. A., and B. A. Nilson. 1982. Radiotelemetry as a means of assessing movement and habitat selection of humpback chub. The American Fisheries Society Bonneville Chapter Proceedings 1982:29-40.

Valdez, R. A., W. J. Masslich, W. C. Leibfried. 1992. Characterization of the life history and ecology of the humpback chub (*Gila cypha*) in the Grand Canyon. Annual Report to Bureau of Reclamation, Contract No. 0-CS-40-09110. BIO/WEST Report No. TR-250-04. 222 pp.

Yoshikawa, H., Yokoyama Y., Ueno S., Mitsuda H. 1991. Changes of blood gas in carp, *Cyprinus carpio*, anesthetized with carbon dioxide. Comparative Biochemistry and Physiology 98A 431-436.